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NO. LED570-1 DATE: 4 March 1963

DETAILED PRESIMULATION REPORT
FØR PHASE A
LUNAR HOVER AND LANDING SIMULATION [U]

~~GROUP 4 Downgraded at 3 year intervals; declassified after 12 years.~~

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PREFACE

This report although prepared by the authors, represents the efforts of many groups over the past several months. The results of these efforts will be a successful Lunar Hover and Landing Simulation Program. The following LEM groups contribute greatly to the simulation program:

Crew Systems
Dynamics and Performance
Weights
Flight Controls

In addition to the above LEM groups, the Engineering Research Department provided analog computers, computer programmers, and the motion simulator for the program; the Flight Test Instrumentation Department provided instrumentation support for the simulation.

Particular appreciation is expressed for the individual contributions of P. Kelly, Dynamics and Performance Group, for his preparation of the simplified flight control system dynamics; S. Salina, Weights Group, for their preparation of the vehicle mass and inertial properties; M. Housner, Engineering Research Department, for his preparation of the problem for the analog computer; R. Moncsko, Flight Test Instrumentation Department, for his preparation of the cockpit display instrumentation and data recording equipment; and to the numerous other personnel assisting in this program.

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GRUMMAN AIRCRAFT ENGINEERING CORPORATION

DETAILED PRESIMULATION REPORT

FOR PHASE A

LUNAR HOVER AND LANDING SIMULATION

SUMMARY

This simulation program will cover the terminal phase of the LEM descent to the lunar surface. The simulation program begins with the LEM at the hover altitude (1,000 ft. above lunar surface) and ends at such time as the LEM vehicle touches down on the lunar surface. The primary objectives of the simulation program are to determine the basic handling qualities of the vehicle and to determine the degree of control required for man to fulfill the required functions of the mission. This simulation will utilize an analog computer to solve the six degree of freedom equations that describe the vehicle dynamics, a motion device will present dynamic cues to the subject, a visual display and cockpit instruments will give visual cues to the subject and cockpit controls will allow the subject to exercise control over the simulated situation.

The study programs to be conducted during this simulation have been outlined by the various System and Sub-System groups. These study programs have been integrated into an overall test program by the Crew Systems Group. The design problems which will be investigated are as follows:

1) Vehicle configuration based upon consideration of descent engine control (gimbaled vs. non-gimbaled) and Reaction Control System operation (rate commanded proportional system vs. direct on-off system). These studies should give an indication of on-board fuel requirements.

2) Vehicle control system configuration as applied to Manual Control and Flying Qualtities analysis. This study should be designed to determine the amount of manual control desired and required to fulfill the requirements of the mission. In addition, it should furnish preliminary information for the development of a suitable flight controls system. The Flight Controls Group has supplied a basic control system for inclusion in the simulation. This system will be expanded to furnish desired information as the actual control system develops

3) The degree of automatic control feasible will be studied by a series of experiments. The prime consideration in this study will be a trade-off investigation of automatic control vs. other semi-automatic and manual modes of control. This investigation should also give an indication

of the on-board fuel requirements.

It is the intention of the simulation program to include revisions, changes, and modifications as they occur in the design of the LEM vehicle and yet maintain an overall integrity to the simulation study. Toward this end, various groups within the LEM organization have been requested to supply new information and requirements to the System Simulation Group as soon as they are generated.

Data from the simulation will be recorded in both analog and digital form. The quantities that are to be used for quantative analysis will be presented in analog form and those required for qualitative analysis will be recorded in digital form. Because this is primarily an analog simulation, conversion equipment will be used to sample the analog voltage and convert it to digital form. This digital equivalent of the analog voltage will then be recorded on either punched paper tape or magnetic tape. This data would then be processed at a later time and compiled into a suitable working format.

The Hover and Landing Simulation program is scheduled to begin operation in early March 1963 and run through the end of April 1963

ASSUMPTIONS

1) To enable the Hover and Landing Simulation to be operational as quickly as possible and yet fulfill the major primary requirements, certain assumptions have had to be made. These assumptions have been made so that the computer program may be kept to a reasonable size and complexity. It is assumed that the hover and landing program will begin after the pilot has selected his landing site. In effect the hover maneuver is just about terminated. With the landing site acquired the pilot is ready to begin his descent from hover. The simulator program will have as initial conditions whatever information is necessary to establish the location of the landing site and the relative position of the LEM vehicle to that landing site.

2) Some type of on-board system to calculate the ground track, target range, vehicle altitude, vehicle-target heading error and other such quantities have been assumed. These items would most probably be calculated by the on-board guidance system in the actual vehicle. Because these studies are to be conducted assuming that the pilot is using a visual contact mode of descent, there has been no attempt to include a guidance scheme any more complex than that which would be necessary to drive the instruments of the motion device. In reality, these would probably be a radar to give altitude and other measuring devices for the remaining instrument drives. As far as the simulation is concerned, all of the required items that must be displayed to the subject are available from the geometry of the system. The required instrument drives are created as an integral part of the computer program and then applied to the proper display in the cockpit.

3) The inertial coupling effects of the main engine gimbaling have not been introduced in the development of the defining equations because of a) the increased degrees of freedom associated with these terms and b) the resulting size and complexity of the computer program should these terms be included.

4) The misalignments of the Reaction Control System jets, as caused by manufacturing inaccuracies, have been assumed negligible.

5) The LEM vehicle is considered to be a rigid body. This assumption does not allow for any deflection or settling of the vehicle as is touches the lunar surface. The landing gear deflection problem will be investigated in another simulation program.

6) The reaction control jets that would impart a translation in the positive and negative x direction are not to be used for translation. This is assumed because for this portion of the mission the main engine is operating and is throttlable. The use of the throttle would allow the vehicle to ascend or descend and this is

equivalent to a translation in the positive and negative x direction. If the x axis reaction jets were used for translation they would not add significantly to the total thrust available.

7) At no time will the reaction control system be called upon to perform both a translation and rotation maneuver at one and the same time. This assumption is required in order to allow the computer program to remain at a reasonable level of complexity for the first simulation. It doesn't seem likely that the pilot would want to perform both a rotation and translation at the same time in the simulated Hover and Landing portion of the mission.

GENERAL

The proposed simulation program for the Hover and Landing portion of the LEM mission has been divided into two Phases. PHASE A is to provide various LEM engineering groups with information that will help determine major design parameters. The PHASE A simulation will be conducted using the Grumman Aircraft Engineering Corporation's Research Department Motion Device. This simulation is scheduled to begin in March 1963 and continue through April 1963. The second portion of the Hover and Landing simulation program, PHASE B, will incorporate all LEM design improvements and modifications. The PHASE B effort will be directed primarily toward actual training and hardware check-out. This PHASE B simulation is scheduled to begin operation in February 1964.

The PHASE A simulation will be a manned study to determine various major design parameters of interest to the Flight Control, Dynamics, Navigation and Guidance, Weights and Crew Systems Groups. The first simulation that will be performed shall investigate the basic handling qualities of the present LEM configuration. Provision has been made through the cooperation of the Structures Group to keep the computer program current with the vehicle configuration at various stages of development. As the geometry of the vehicle changes the Structures Group will notify the Systems Simulation Group and at the appropriate time the simulation will be updated to conform with the design changes. It must be pointed out that should the Crew Systems Group be running a series of experiments such that any change in the computer program would effect the validity of the results, these changes will be made at the first appropriate opportunity. It is the intention of the PHASE A simulation program to allow for as much flexibility as possible and yet keep a reasonable size and complexity.

There will be no attempt to study the visibility limitations of the LEM vehicle because the Motion Device is a single seat unit and the actual LEM is a two place module. In order to accurately investigate the visibility problems, a two place crew station is required. The visibility problems will be investigated at a later date with the aid of a two place crew station or its equivalent.

There will be no attempt to study abort trajectories during the PHASE A simulation program. An abort trajectory analysis would probably require the LEM vehicle to experience larger and more violent manuvers than would be studied in a preliminary analysis of the vehicle handling qualities. There is also the possibility that these manuvers would exceed the limits of the motion device. Should the limits of the motion device be exceeded then the computer would be placed into reset and at that point the computer solution would end. It should be pointed out that the Hover and Landing simulation will give an indication of abort manuvering capability during the descent from hover portion of the LEM mission, should it be desired.

The study programs to be conducted in PHASE A will be outlined by the respective groups and will be integrated into the overall simulation plan by the Crew Systems Group. Every attempt will be made to provide the required data in a form that will be most meaningful and useful to the specific group that has requested it. At present, it is planned to provide both analog and digital data outputs.

The Crew Systems Group has prepared an experimental test program. This test program is divided into two major parts (manned and unmanned). The data to be recorded in the manned simulations will be directed toward improving the man - vehicle relationship. The unmanned mode of operation will be used to evaluate various modes of automatic operation. The PHASE A program places most of the emphasis on the manned program. Various modes of control system configuration will be used to evaluate the subjects ability to fulfill the requirements of a safe landing on the lunar surface.

The Dynamics Group has prepared the necessary equations for simulating the vehicle dynamics. These equations are written in general form and contain the full six degrees of freedom. At present an analysis is being conducted to determine if any of the terms are of such small magnitude that they may be safely neglected in the simulation. The roll, yaw and pitch order of rotation used in the development of the equations, although contrasting with the standard LEM sequence of pitch, yaw and roll (as per LEM ENGINEERING MEMO L500-M03-2) was necessary to accomodate the motion device and visual display. The motion device and visual display first presents roll to the subject in the form of a left-right translation of the lunar landscape on a TV type projection screen. Yaw is then accomplished by differential linear vertical translations. These translations take place on the two forward posts of the motion device. The cockpit is then pitched by means of a third vertical translation on the post aft of the seat. This pitch motion is accomplished about the carried pitch axis. If the seat were pitched prior to yaw (in the standard LEM Euler angle sequence) this would necessitate translations in a direction other than vertical in order to accomodate yaw about the carried yaw axis. The presently available motion device is capable of only vertical translations.

For a complete description of the motion device the reader is directed to a report issued by the Research Department concerning this device.

The actual equations that are used in the simulation are written in general form and are in agreement with those in WADD TECHNICAL REPORT 60-781. Euler angle rotation equations were derived by means of matrix and vector methods. The system equations take into account jet damping effects (as per WADD TECHNICAL REPORT 60-781), a gimbaled main engine, changing moments of inertia, products of inertia (where significant), and C.G. location due to propellent burning. Calculations of Range, Azimuth and Elevation angles, and Line-of-Sight variables (Heading Error, Line-of-Sight, Ground Track and Normal and Tangential Velocity components) are included to meet the requirements of the usual display and cockpit instruments.

The required Reaction Control System Equations were also developed by the Dynamics Group. These equations assumed that all jets are activated in pairs for translation and rotation, thus disqualifying the case of unbalanced torques other than those induced by the translational or rotational manuver.

The Flight Controls Group is developing an experimental test program to determine the required information on the basic handling qualities of the vehicle. This test program will be integrated with the one developed by the Crew System Group. This integration is necessary to properly determine the man-vehicle performance. The data obtained for the Flight Controls Group will be of primary value in determining some of the Sub-System design parameters.

In order to adequately determine the LEM manuvering capabilities and handling qualties, several extreme landing procedures are postulated. These include a 1000 ft. minimum time translation using a maximum vehicle attitude of 15 degrees in pitch, and a minimum time vertical descent from a 2000 ft. altitude. The scaling in the simulation should be capable of providing the above requirements. In these manuvers conducted for the Flight Controls Group as well as for all other experiments the primary technique for translation control will be provided by pitching the vehicle and utilizing a component of the main engine thrust vector.

The Navigation and Guidance Group has been consulted to determine if the method of calculation for quantities that drive the cockpit instruments violates any of the guidance schemes under consideration. Information from them indicates that the method used to obtain these quantities is satisfactory for use at this time. If any developments should change this decision the Navigation and Guidance Group will notify the System Simulation Group and the proper changes will be made to the simulation program.

The Weights Group has provided the mass and inertia properties for the simulation of the LEM vehicle. This data gives the nominal value and an expected range for the values. The simulation program is set up to handle the ranges as specified by the Weights Group. This group has also been advised to keep the System Simulation Group informed should the values under consideration exceed the presently specified maximum or minimum value.

The required ranges of the variable and parameter values that are necessary for the simulation program have been supplied by the various groups directly concerned with them. These groups have also been directed to supply any change in range or value to the Simulation Group for inclusion in the simulation program as it is updated.

These changes are necessary if the simulation program is to remain current with the acutal LEM design configuration as it develops and is firmed up. Every attempt will be made to update the simulation as often as possible and yet maintain the overall integrity of the prepared schedule of experiments.

COCKPIT INSTRUMENTATION

The motion device cockpit instrumentation consists of both panel instruments and vehicle flight controls. The panel instruments, consist of both synchro and galvanometer type instruments. The vehicle flight controls are composed of an engine throttle and a three axis controller. The panel instruments provide visual cues to the pilot and the flight controls allow the subject to exercise control over the simulated situation. The quantities displayed to the subject via the instrument panel and the type of instrument used are as follows:

QUANTITY DISPLAYED	INSTRUMENT TYPE
Range to go	synchro
Heading error	synchro
Roll angle	synchro
Yaw angle	synchro
Pitch angle	synchro
Closing translational rate	meter
Lateral translational rate	meter
Vertical velocity	meter
Roll rate	meter
Yaw rate	meter
Pitch rate	meter

The vehicle flight controls that are present in the motion device cockpit are a main engine throttle and a three-axis fingertip controller. The fingertip controller allows for the control of the Reaction Control System jets to provide attitude control of the vehicle. The yaw altitude is controlled by a left-right movement of the controller arm, the pitch attitude is controlled by a fore and aft motion of the arm and the roll is controlled by twisting the controller arm. The three axis controller is mounted on the right side of the cockpit and an arm rest is provided to insure that the controller is operated in the correct manner prescribed for a fingertip controller. If necessary, provision has been made to physically restrain the subjects forearm so that he may use only his fingertips in the operation of the controller.

The throttle control allows the main engine thrust level to be continuously variable from minimum thrust (1050 pounds) to maximum thrust (10,500 pounds). The motion of the throttle is fore and aft. The full forward position is equivalent to the maximum thrust and the full aft position represents minimum thrust. There is a four way switch mounted atop the throttle handle and this device controls relays that allow the reaction jets to be used for translation in the Y-Z plane of the system. This translation is in the fore and aft as well as the side to side direction. The main engine throttle control is located to the left of the pilot and opposite the fingertip controller

It should be pointed out that there is no provision for the institution of both a translation and rotation at the same time using only the reaction jets. The computer will not process these commands if they occur simultaneously. The training schedule for the pilots will insure that they observe the requirement of commanding either a translation or rotation but not both at the same time.

It has been requested that the use of reaction jets for translation impart no rotation to the simulation and that when they are used for rotation that there be no translation introduced into the system. This request has been honored and the system will operate in the desired manner.

There are three toggle switches that are mounted on the instrument panel. These switches allow the roll, yaw and pitch attitude control jets to be operated in either the rate commanded proportioned mode or the direct on-off mode. The rate commanded proportional mode is a simplified form of a pulse width and pulse frequency modulated control system. The initial minimum pulse bit is increased in frequency until the limit frequency of the system is reached. At such time as this occurs the pulse width is increased at that frequency until finally the reaction control jet is on all of the time. In the simulation program a function that represents the impulse of the control system is used and the area of the simulated function is equivalent to the area of the pulses that would be present should the actual pulse train be generated and then integrated.

The direct on-off mode when selected will be a bang - bang type of operation. As soon as the controller is moved out of the dead-band the reaction jets affected will be turned on. The actual controller being used is spring loaded to the neutral position. If the controller is displaced and then released it will return to the neutral position because of the restoring force presented by the spings attached to the controller arm.

EQUIPMENT

The equipment that will be used for the actual simulation is composed of two analog computers, a motion device and a visual display.

COMPUTATION

The analog computers are used to solve the six degree of freedom equations and to accomplish the various calculations that would be normally performed on-board the actual vehicle. The calculated values are then applied to the motion device, cockpit instruments and visual display to present the subject with the simulated situation. The subject then interprets these cues and determines what control actions if any should be taken. If a control function is indicated then the subject will perform the task with the controls present in the simulator cockpit. These control actions are then applied to the computer. The computer then operates on these inputs and presents the new situation to the subject. This method of operation continues until a landing on the lunar surface has been accompolished.

VISUAL DISPLAY

The visual display presents a lunar landscape to the subject. The landscape is drawn on a flat metal plate and placed in the system. There is a light source that is moved vertically as a function of vehicle altitude. As the vehicle descends toward the lunar surface the light source is driven toward the image plate. The motion simulates the visual equivalent of an actual descent. The simulation of roll is accomplished by a rotation of the lunar landscape. The image table of the visual display is servo driven and rotates in conjunction with the roll angle calculated in the computer and displayed in the cockpit. The visual display is also capable of lateral and longitudinal translation. In reality the visual display presents four of the simulated six degrees of freedom (three translational degrees of freecom and one rotational degree of freedom).

MOTION DEVICE

The motion device is used to present the remaining rotational degrees of freedom to the subject. The motion device is driven from a safety console that is in close proximity to the actual motion device. Under normal operation the safety console is merely an interface between the motion device and the computers. In the event of a failure or other such circumstance the safety console has control over the entire simulation and is capable of terminating it at any point of the run. This safety console actually begins the simulation operation so as to insure the safety of the subject. Because the computers are located in a room removed from the motion device an intercom is provided to insure that the safety of the subject is maintained.

The motion device is capable of providing plus and minus 15 degrees of pitch and plus and minus 25 degrees of yaw. The yaw motion is defined in term of the LEM axis system. If this were referenced to the normal aircraft axis system the pitch definition would remain unchanged but the angular displacement that is defined as yaw for the LEM would become roll. These angular motions are accomp-lished in conjunction with a plus or minus 3 foot vertical motion. For a detailed description of the motion device the reader is referred to a Grumman Research Department publication entitled "The Grumman Motion Simulator".

DATA OUTPUT

The main function of the simulation program is to provide meaningful data to the various LEM engineering groups that have requested some experimental design parameters and also to provide Crew Systems with data that would be helpful in determining the man-vehicle performance and requirements. The data will be recorded in both analog and digital form. The analog data will be used for quantative analysis and the digital data will be used to perform qualitative analysis. This data will be presented to the respective engineering groups in a form that will aid them in their analysis of the vehicle. The actual detailed analysis will be conducted by the respective System and Sub-System engineering Groups.

The analog data will be in the form of time history recordings. These recordings present numerous variables recorded as functions of time. The analog recorders begin operation at the beginning of the simulator run and stop at such time as the run is completed. The outputs of each run that are recorded in this manner are available immediately for observation and preliminary analysis. The quantities that are recorded as time histories are those that are required to determine the dynamic behavior of the vehicle as well as those which are required to determine if the subject has performed the mission within the major limits of the experiment design. The time history recordings also give an indication as to the basic frequencies that may be encountered in various modes of operation.

The digital output will be formed by sampling various quantities in the simulation, converting them to digital form with the use of analog to digital converters, recording this data on paper or magnetic tape and finally by printing out the prepared data tape. This data will not be immediately available for use as there is a time factor required for the processing of the tape to printed format. This time factor should not be of significant effect to the overall analysis of the system. The reason for the delay in the processing of the data tape is that it is more time consuming than the actual recording time. It appears to be more efficient to process a group of runs that have been performed as the experiment schedule defines them and publish all of the data concerned with that section of the experimental test plan. Another factor which dictates this mode of operation is that it is more desire-able to store one reasonably large roll of recorded data rather than many small ones. It is also easier to perform data analysis when one has available a group of related runs rather than a number of independent or effectively independent runs.

EXPERIMENTAL TEST PLAN

The experimental test plan has been prepared by the Crew Systems Group. This test plan incorporates the basic requirements of all the LEM engineering groups that have requested data from the Hover and Landing Simulation program. A discussion of the experimental test plan and the test plan as developed by Crew Systems follows:

STUDY OUTLINE

LUNAR LANDING SIMULATION

I. Purpose -

This study is intended to determine those LEM vehicle handling characteristics which will provide the optimum control configuration that allows the pilot to guide the vehicle to a successful lunar landing. For this initial phase of study, variations will be introduced in the Reaction Control System Modes, main engine configuration employed and in the damping ratios of one of the RCS modes.

The landing phase for purposes of the LEM mission is initiated at a hover altitude of 1000 ft. and within a 1000 ft. horizontal displacement from the target area, selected for touchdown. The vehicle would be manually guided by the pilot throughout this phase, since conditions and characteristics of the lunar terrain could not reasonably be anticipated in precise enough detail to allow an automatically controlled descent. Even if such a automatic guidance system were employed, its failure to function would still require a suitably designed manual control system to allow the pilot to effect a landing within a specific performance envelope.

The results of the present study should aid in developing optimum vehicle control characteristics and in defining those aspects of the manual control system which require more detailed study in the later simulation phases.

II Method -

The experimental variables to be studied and the way in which they will be varied are as follows:

1. RCS Mode:

   a. Proportional Mode - Rate command proportional to attitude controller position.

   b. Direct Mode - Non-proportional acceleration command, with acceleration rate constant. (On-Off Control)

2. Main Engine Configuration:

   a. Main engine gimballed

   b. Main engine fixed

3. Horizontal Displacement from Target

   a. Near - Initial position 200 ft. horizontal displacement.

   b. Far - Initial position 1000 ft. horizontal displacement.

   Under only the proportional RCS mode, variation in damping ratios will be introduced in the following way:

   Damping Ratio - Four (4) sets of ratios, each with a set of values established for pitch, roll and yaw (as shown in Table I).

   a. Low Ratio

   b. Medium Ratio

   c. High Ratio

   d. Analytical Estimate (Best analytical estimate for optimum damping ratio.)

   Measures of Pilot Performance

   The following constitute the measures that will be obtained from each simulation trial in order to evaluate control suitability under the above experimental conditions:

   a. Main Engine fuel consumed per foot of vehicle slant range. (lb ./ft)

   b. RCS fuel comsumed per sq. ft. deviation from optimum flight path.

   c. Total flight path deviations from an optimum path.

   d. Total deviations from center of target area at touchdown.

   e. Terminal resultant linear velocity and acceleration.

   f. Terminal attitude and attitude rates.

   g. Pilot evaluations of control configuration.

III Procedure -

1. Preliminary

Subjects will be given an indoctrination on the techniques of lunar landing, vehicle control modes, control characteristics, utilization of the cockpit displays, etc. This is to be done by: (a) Film, (b) Lecture and (c) Introduction to the simulator and its handling qualities.

Following these there will be a:

<u>Pre-Training Period</u> - Each pilot will be required in pre-trial training sessions to guide the vehicle to two successful lunar landings. Once by use of the proportional RCS control mode and once by use of the direct RCS mode. The initial position for the pre-training runs will differ from the two positions selected for the experimental trials. Each subject would complete a minimum of 4 pre-training trials. The series of trials would continue until the subject achieves the 2 successful landings (one for each RCS control mode) and within a time criterion of 120 seconds. Initial conditions for each of the set of trials is shown in Table I.

The intent is to begin the experimental trials with subjects equal to some degree, on landing skill. It is also assumed that the time criterion can be met in a "reasonable" number of pre-training trials.

2. <u>Experimental Trials</u>

A minimum of 3 subjects would be required, each of whom would complete 40 trials (20 conditions; 2 trials per condition for each subject). Table II establishes the initial conditions necessary for each run. It is intended that the first 20 trials, for each subject, be carried out in the order shown and the next set of 20 in reverse order. Following each trial, the subject will evlauate the accptability of the control system on a Cooper scale.

Five minute breaks should be allowed between every 6 or 7 trials with a ten minute break after the first 20 trials.

Instructions to the subjects would be as follows:

"Your task in each of the following trials is to land as near the target area as you can and as quickly as possible. Maintain visual contact with the target area until you are 25 ft. above the point of touchdown, at which time you will hover and descend vertically to a landing.

You must accomplish the landing as quickly as possible. On tounching down your vertical velocity must be no greater than 10 feet per sec. Your horizontal velocity no greater than 5 feet per sec. with your attitude no greater than $\pm 5^{\circ}$ and an angular rate no greater than 9°/sec. Certain control characteristics will vary on each trial as will your starting position above the target area, but the task is still to land as near the target as you can and to touchdown as quickly as possible."

IV Data Analysis

The design of the study is shown in Table III.

Two separate statistical analyses are required. One is a comparison of Engine Confiugration; Damping Ratio and Target Displacement for the RCS Proportional Mode (2 x 4 x 2 = 16 conditions). The second analysis is a comparison of Direct and Proportional RCS modes; Engine Configuration and Target Displacement (2 x 2 x 2 = 8 condition).

These data allow for determinations of which (if any) of the variations of the experimental conditions yield superior landing control by the pilot (e.g., whether gimballed engine is significantly superior to fixed engine; proportional RCS mode superior to Direct Mode, etc.). In addition it will be possible to determine whether several variables interact in a significant manner (e.g., whether a given target displacement in conjunction with a given engine configuration and RCS mode results in a significant effect on achieving land). The relationships between damping ratio level and the various performance measures will also be obtained.

In addition, reliability values will be obtained for the Cooper rating scales and the scale scores will be correlated with each of the performance measures.

TABLE I

14	15	16	17	18	19	20					
								* R= RED		B=BLUE	
A	O	A	O	O	O	O		A =	0.7320		
B	O	B	O	O	O	O		B =	0.0651		
3.5	3.5	1.0	1.0	3.5	1.0	3.5					
3.5	3.5	1.0	1.0	3.5	1.0	3.5					
L	R	L	R	R	R	R		L= GIMBALLED ENGINE			
L	R	L	R	R	R	R		R = FIXED ENGINE			
P	P	D	P	P	P	P	P= PROPORTIONAL				
Lo	Lo	O	M	M	Lo	AN	D= DIRECT				
							M= MEDIAN				
							H = HIGH				
							AN = ANALYSIS ESTIMATE				
							Lo= LOW				
1	1	2	2	1	2	1					

REPORT: LED570-1
DATE: 4 March 1963

CREW SYSTEMS
25 FEB 63
28 FEB 63 REV A

SUMMARY OF DEAD-BANDS, GAINS, & TIME CONSTANTS TO BE INVESTIGATED

PHASE A LUNAR LANDING AND HOVER SIMULATION

QUANTITY	MEDIAN	HIGH	ANALYSIS EST.	LOW
K	0.398	0.166	1.590	12.740
n	0.090	0.061	0.090	0.180
τ_f	0.040	0.040	0.040	0.040
k_1	0.000	0.000	0.000	0.000
k_2	0.150	0.150	0.150	0.150
K_c	10.000	10.000	10.000	10.000
$K_{R\phi}$	0.784	1.000	0.392	0.196
$K_{P\phi}$	0.500	0.339	0.500	1.000
$K_{R\theta}$	0.784	1.000	0.392	0.196
$K_{P\theta}$	0.500	0.339	0.500	1.000
$K_{R\psi}$	0.784	1.000	0.392	0.196
$K_{P\psi}$	0.500	0.339	0.500	1.000

Sequences 8

A (Median) runs 1, 2, 6, 9, 11, 16, 17, 18

B (High) runs 2, 3, 5, 6, 7, 11, 13, 16

C.(Analysis) runs 2, 4, 6, 8, 10, 11, 16, 20

D (Low) runs 2, 6, 11, 12, 14, 15, 16, 19

TABLE II

LUNAR LANDING SIMULATION PRE-TRIAL CONDITIONS

MACHINE	POT NOS	SYMBOL	SCALE	VALUE	PRE TRIAL 1	PRE TRIAL 2	PRE TRIAL 3	PRE TRIAL 4
R	P16	θ	1/200	0	0	0	0	0
R	P18	ϕ	1/200	45°	.2250	.2250	.2250	.2250
R	P17	ψ	1/200	0	0	0	0	0
R	P15	$\sin\delta\theta_m$	8	.09150	0	0	.7320	.7320
B	Q00	$\sin\delta\psi_m$	8	.00814	0	0	.0651	.0651
B	P38	I_{xx}	1/10^4	5862	.5862	.5862	.5862	.5862
B	Q48 P49	I_{yy}	1/10^4	6185	.6185	.6185	.6185	.6185
B	P47	I_{zz}	1/10^4	6370	.6370	.6370	.6370	.6370
B	Q26 Q28 P36	I_{xy}	1/10^4	-78.21	-.007821	-.007821	-.007821	-.007821
B	P22	I_{xz}	1/10^4	140	.0140	.0140	.0140	.0140
B	P25, P26 P30, Q30 P33, P39	I_{yz}	1/10^4	-94.92	-.009492	-.009492	-.009492	-.009492
B	P15	m	1/500	337	.6740	.6740	.6740	.6740
B	Q04	R_x	1/200	1000	5.0	5.0	5.0	5.0
B	Q06	R_y	1/200	500	2.5	2.5	2.5	2.5
B	Q07	R_z	1/200	500	2.5	2.5	2.5	2.5
R	FS10	MAIN ENGINE			R	R	L	L
B	FS10				R	R	L	L
	J-G1121	RCS			P	D	P	D

NOTE: SEE RUN SCHEDULE FOR SYMBOL DEFINITIONS. DAMPING RATIOS WILL BE THE SET DETERMINED BY ANALYSIS.

C.S.
28 FEB '63

REPORT: LED570-1
DATE: 4 March 1963

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TABLE III

EXPERIMENTAL PLAN

PROPORTIONAL MODE																DIRECT MODE			
Main Engine Fixed								Main Engine Gimballed								Main Engine Fixed		Main Engine Gimballed	
Target Displacement								Target Displacement								Target Displacement		Target Displacement	
200 Feet				1000 Feet				200 Feet				1000 Feet				200 Feet	1000 Feet	200 Feet	1000 Feet
Damping Ratio				Damping Ratio				Damping Ratio				Damping Ratio							
LOW	MED	HI	AE	LOW	MED	HI	AE	LOW	MED	HI	AE	LOW	MED	HI	AE				

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CONCLUSION

The Hover and Landing Simulation program has been designed and developed to fulfill all of the basic requirements for an engineering design program and where possible has been expanded to permit more extensive experimental study. Because this is a basic design study there has been no attempt to instrument the simulator with the actual instruments that will be on-board the vehicle. Instead the major effort has been expanded on the development of the equations. These equations have been developed in a manner such that all of the requested experiments are able to be performed with a minimum of delay between them. Parameters have been kept separate where possible in order to allow for the rapid changes from one set of conditions to another. The instruments have been studied and found to perform adequately for the type of experiments being conducted.

The simulation program as it is presently designed and the experimental test plan as set up, should adequately fulfill all of the initial requested parameter studies as indicated by the various LEM engineering groups. During the simulation program it is expected that additional study areas will be uncovered and integrated into the overall test program. As this simulation is basically an engineering design program additional study requirements will also be generated as actual vehicle design progresses. It is presently anticipated that the following areas will be investigated during the Phase A Simulation program.

1) Flight Control studies consisting of
   a) Control Power Variation
   b) Anagular Velocity Damping
   c) Altitude Hold Dead-Band
   d) Rate (Stab. Augment) Dead-Band
   e) Controller Dead-bands and Sensitivity

2) Abort sequencing during landing

3) Simulated malfunctions such as engine gimbal run-away, loss of rate feedback, RCS failure modes, instrument display failures, etc.

4) Investigation of various Lunar landing techniques, manned and unmanned operation.

5) Investigation of a fully proportional gimballed descent engine for maneuvering.

6) Use of Phase A landing simulation to simulate portion of powered descent trajectory from 20 miles down to hover point. Evaluation of various radar schemes to be used for the descent trajectory.

APPENDICIES

The following is a list of appendices included in this report. These appendices are normally generated during the build up of a simulation program and as such are in reality work sheets for the simulation problem. They are included in this report exactly as generated for the simulation program as an indication of the method used in building the Hover and Landing Simulation program:

APPENDIX NO.	DESCRIPTION
I	Equation Summary for Hover and Landing Simulation
II	Definition of Constant and Variable Quantities.
III	Definition of LEM Geometry and Schematic Computer Flow Chart.
IV	Simplified Flow Diagrams a) Flow Chart for System Equations b) Interface Flow Diagram
V	Summary of Defined Constant Values.
VI	Summary of Variable and Parameter Scaling.
VII	Detailed Analog Computer Flow Chart.
VIII	Analog Computer Program.
IX	Analog Computer Parameter Sheets.
X	Photographs of the Hover and Landing Simulator a) Instrument Panel b) Cockpit Layout c) Analog Computers.
XI	Comparison of LEM Flight Controls System and Flight Controls System used for Lunar Landing Simulation

APPENDIX NO. I

EQUATION SUMMARY FOR HOVER AND LANDING SIMULATION

SUMMARY OF THE EQUATIONS FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

NOTE: THE EULER ORDER OF ROTATION IS DEFINED TO BE $\phi \rightarrow \psi \rightarrow \theta$. THIS IS A DEPARTURE FROM THE ORDER USED IN THE RENDEZVOUS AND DOCKING SIMULATION. THIS DEPARTURE IS NECESSARY BECAUSE THERE ARE RESTRICTIONS IN THE PRESENTLY AVAILABLE MOTION DEVICE THAT MUST BE RESPECTED.

I. BODY AXIS TRANSLATION EQUATIONS

$$B_x = m(\dot{u} - vr + wq) + mg\,l_1$$

$$B_y = m(\dot{v} - wp + ur) + mg\,m_1 - 2\dot{m}\,r\,l_D$$

$$B_z = m(\dot{w} - uq + vp) + mg\,n_1 + 2\dot{m}\,q\,l_D$$

WHERE:
1) l_1, m_1, AND n_1 ARE DIRECTION COSINES.
2) g = MOON GRAVATATIONAL CONSTANT $\approx$ 1/6 EARTH GRAVITY.
3) m = MASS OF THE VEHICLE.
4) p, q, AND r ARE BODY ROTATION VELOCITIES.
5) u, v, AND w ARE BODY TRANSLATION VELOCITIES.
6) $\dot{u}$, $\dot{v}$, AND $\dot{w}$ ARE d/dt OF u, v, AND w RESPECTIVELY.
7) B_x, B_y, AND B_z ARE THE SUMMATION OF FORCES IN THE x, y, AND z (BODY AXES) DIRECTIONS RESPECTIVELY.
8) l_D IS JET DAMPING LENGTH = CONSTANT. (x-z PLANE)
9) $\dot{m}$ IS TIME RATE OF CHANGE OF VEHICLE MASS

II. INERTIAL TRANSLATION EQUATIONS

$$V_X = l_1 u + m_1 v + n_1 w$$

$$V_Y = l_2 u + m_2 v + n_2 w$$

$$V_Z = l_3 u + m_3 v + n_3 w$$

WHERE:
1) l_1; l_2; l_3; m_1; m_2; m_3; n_1; n_2 AND n_3 ARE DIRECTION COSINES.
2) u; v AND w ARE BODY TRANSLATION VELOCITIES.
3) V_X; V_Y AND V_Z ARE THE VELOCITIES IN THE X; Y AND Z (INERTIAL) DIRECTIONS RESPECTIVELY.

EQUATION SUMMARY FOR HOVER AND LANDING SIMULATION CONTINUED

III.

DIRECTION COSINE EQUATIONS (EULER ORDER $\phi \to \psi \to \theta$)

$$\ell_1 = \cos\theta \cos\psi$$
$$\ell_2 = \cos\theta \sin\psi \cos\phi + \sin\theta \sin\phi$$
$$\ell_3 = \cos\theta \sin\psi \sin\phi - \sin\theta \cos\phi$$
$$m_1 = -\sin\psi$$
$$m_2 = \cos\psi \cos\phi$$
$$m_3 = \cos\psi \sin\phi$$
$$n_1 = \sin\theta \cos\psi$$
$$n_2 = \sin\theta \sin\psi \cos\phi - \cos\theta \sin\phi$$
$$n_3 = \sin\theta \sin\psi \sin\phi + \cos\theta \cos\phi$$

IV.

EULER RATE AND ANGLE EQUATIONS (EULER ORDER $\phi \to \psi \to \theta$)

$$\dot{\phi} = \frac{p\cos\theta + r\sin\theta}{\cos\psi}$$

$$\dot{\psi} = r\cos\theta - p\sin\theta$$

$$\dot{\theta} = q + \frac{\sin\psi\,(p\cos\theta + r\sin\theta)}{\cos\psi} = q + \sin\psi\,(\dot{\phi})$$

$$\phi = \phi_0 + \int_0^t \dot{\phi}\,dt$$

$$\psi = \psi_0 + \int_0^t \dot{\psi}\,dt$$

$$\theta = \theta_0 + \int_0^t \dot{\theta}\,dt$$

WHERE: 1) ϕ_0; ψ_0 AND θ_0 ARE THE INITIAL VALUES OF ϕ, ψ AND θ RESPECTIVELY.

2) p, q AND r ARE THE BODY ROTATION VELOCITIES

3) THE UPPER LIMIT OF THE INTEGRALS SIGNIFIES THAT THE DERIVATIVES OF THE RESPECTIVE VARIABLES ARE INTEGRATED THROUGHOUT THE ENTIRE PROBLEM SOLUTION TIME.

[redacted]

EQUATION SUMMARY FOR HOVER AND LANDING SIMULATION CONTINUED

V. BODY FORCE AND MOMENT EQUATIONS

$$B_x = T_m \cos\delta_{\theta m} \cos\delta_{\psi m} + T_{jx}$$

$$B_y = T_m \sin\delta_{\psi m} + T_{jy}$$

$$B_z = T_m \sin\delta_{\theta m} \cos\delta_{\psi m} + T_{jz}$$

$$L = T_m (y_m \sin\delta_{\theta m} \cos\delta_{\psi m} - z_m \sin\delta_{\psi m}) + L_j$$

$$M = T_m (z_m \cos\delta_{\theta m} \cos\delta_{\psi m} - x_m \sin\delta_{\theta m} \cos\delta_{\psi m}) + M_j$$

$$N = T_m (x_m \sin\delta_{\psi m} - y_m \cos\delta_{\theta m} \cos\delta_{\psi m}) + N_j$$

WHERE:
1) T_m = MAIN ENGINE THRUST.
2) $\delta_{\theta m}$ = MAIN ENGINE GIMBAL ANGLE ABOUT BODY y AXIS.
3) $\delta_{\psi m}$ = MAIN ENGINE GIMBAL ANGLE ABOUT CARRIED BODY z AXIS.
4) T_{jx} = SUM OF x AXIS REACTION JET THRUST COMPONENTS.
5) T_{jy} = SUM OF y AXIS REACTION JET THRUST COMPONENTS.
6) T_{jz} = SUM OF z AXIS REACTION JET THRUST COMPONENTS.
7) x_m = x AXIS DISTANCE BETWEEN C.G. + MAIN ENGINE GIMBAL AXIS POINT.
8) y_m = y AXIS DISTANCE BETWEEN C.G. + MAIN ENGINE GIMBAL AXIS POINT.
9) z_m = z AXIS DISTANCE BETWEEN C.G. + MAIN ENGINE GIMBAL AXIS POINT.
10) L_j = SUM OF REACTION JET THRUST MOMENTS ABOUT x AXIS.
11) M_j = SUM OF REACTION JET THRUST MOMENTS ABOUT y AXIS.
12) N_j = SUM OF REACTION JET THRUST MOMENTS ABOUT z AXIS.
13) B_x = SUM OF THRUST FORCES IN BODY x AXIS DIRECTION.
14) B_y = SUM OF THRUST FORCES IN BODY y AXIS DIRECTION.
15) B_z = SUM OF THRUST FORCES IN BODY z AXIS DIRECTION.
16) L = SUM OF THRUST MOMENTS ABOUT BODY x AXIS.
17) M = SUM OF THRUST MOMENTS ABOUT BODY y AXIS.
18) N = SUM OF THRUST MOMENTS ABOUT BODY z AXIS.

VI. BODY AXIS ROTATION EQUATIONS

$$I_{xx}\dot{p} = -(I_{zz} - I_{yy})qr + I_{yz}(q^2 - r^2) + I_{xz}(\dot{r} + pq) + I_{xy}(\dot{q} - pr)$$

$$+ p\dot{m}\, l_{D_p}^2 + L$$

[redacted]

EQUATION SUMMARY FOR HOVER AND LANDING SIMULATION CONTINUED

VI BODY AXIS ROTATION EQUATIONS CONTINUED

$$I_{yy}\dot{q} = -(I_{xx}-I_{zz})pr + I_{xz}(r^2-p^2) + I_{xy}(\dot{p}+qr) + I_{yz}(\dot{r}-pq)$$
$$+ q\dot{m}\,l_{D_{qr}}^{2} + M$$

$$I_{zz}\dot{r} = -(I_{yy}-I_{xx})pq + I_{xy}(p^2-q^2) + I_{xz}(\dot{p}-qr) + I_{yz}(\dot{q}+pr)$$
$$+ r\dot{m}\,l_{D_{qr}}^{2} + N$$

WHERE :
1) I_{xx} = MOMENT OF INERTIA ABOUT BODY x AXIS
2) I_{yy} = MOMENT OF INERTIA ABOUT BODY y AXIS
3) I_{zz} = MOMENT OF INERTIA ABOUT BODY z AXIS
4) I_{xy} = PRODUCT OF INERTIA ABOUT BODY x-y AXES
5) I_{xz} = PRODUCT OF INERTIA ABOUT BODY x-z AXES
6) I_{yz} = PRODUCT OF INERTIA ABOUT BODY y-z AXES
7) p = ANGULAR VELOCITY ABOUT BODY x AXIS
8) q = ANGULAR VELOCITY ABOUT BODY y AXIS
9) r = ANGULAR VELOCITY ABOUT BODY z AXIS
10) $\dot{p}$ = ANGULAR ACCELERATION ABOUT BODY x AXIS
11) $\dot{q}$ = ANGULAR ACCELERATION ABOUT BODY y AXIS
12) $\dot{r}$ = ANGULAR ACCELERATION ABOUT BODY z AXIS
13) $\dot{m}$ = TIME RATE OF CHANGE OF VEHICLE MASS
14) $\tilde{l}_{D_{qr}}$ = CHARACTERISTIC DISTANCE SQUARED FOR JET DAMPING (x-z PLANE
15) L = SUM OF THRUST MOMENTS ABOUT BODY x AXIS
16) M = SUM OF THRUST MOMENTS ABOUT BODY y AXIS
17) N = SUM OF THRUST MOMENTS ABOUT BODY z AXIS
18) l_{D_p} = CHARACTERISTIC DISTANCE FOR JET DAMPING (y-z PLANE)

VII. MAIN THRUST MOMENT ARM EQUATIONS

$$x_m = x_{T_m} - \bar{x}_{CG}$$

$$y_m = y_{T_m} - \bar{y}_{CG}$$

$$z_m = z_{T_m} - \bar{z}_{CG}$$

VII. MAIN THRUST MOMENT ARM EQUATIONS CONTINUED

WHERE: 1) x_{T_m} = x- AXIS DISTANCE BETWEEN REFERENCE POINT AND MAIN ENGINE GIMBAL AXIS POINT.

2) y_{T_m} = y- AXIS DISTANCE BETWEEN REFERENCE POINT AND MAIN ENGINE GIMBAL AXIS POINT.

3) z_{T_m} = z- AXIS DISTANCE BETWEEN REFERENCE POINT AND MAIN ENGINE GIMBAL AXIS POINT.

4) $\bar{x}_{CG}$ = x-AXIS DISTANCE BETWEEN C.G. AND REFERENCE POINT.

5) $\bar{y}_{CG}$ = y-AXIS DISTANCE BETWEEN C.G. AND REFERENCE POINT.

6) $\bar{z}_{CG}$ = z-AXIS DISITANCE BETWEEN C.G. AND REFERENCE POINT.

7) x_m = x AXIS DISTANCE BETWEEN C.G. AND MAIN ENGINE GIMBAL AXIS POINT.

8) y_m = y- AXIS DISTANCE BETWEEN C.G. AND MAIN ENGINE GIMBAL AXIS POINT.

9) z_m = z-AXIS DISTANCE BETWEEN C.G. AND MAIN ENGINE GIMBAL AXIS POINT.

IX. MASS AND C.G. CALCULATION EQUATIONS

$$I_m = \int_0^t T_m \, dt$$

$$I_j = \int_0^t (\Sigma T_j) \, dt$$

NOTE: UPPER LIMIT OF INTEGRAL SIGNIFIES THAT THE QUANTITY IS INTEGRATED OVER THE ENTIRE LENGTH OF THE COMPUTER SOLUTION.

$$\Delta m_m = I_m / C_m$$

$$\Delta m_j = I_j / C_j$$

$$\dot{m}_m = T_m / C_m$$

$$\dot{m}_j = (\Sigma T_j) / C_j$$

$$\dot{m} = -\dot{m}_m - \dot{m}_j$$

$$\Delta m = \Delta m_m + \Delta m_j$$

$$m = m_0 - \Delta m$$

$$\bar{x}_{CG} = \bar{x}_{CG_0} - \left(\frac{d \bar{x}_{CG}}{d m} \right) \Delta m$$

EQUATION SUMMARY FOR HOVER AND LANDING SIMULATION CONTINUED

VIII. MASS AND C.G. CALCULATION EQUATIONS CONTINUED

$$\bar{y}_{CG} = \bar{y}_{CG_0} - \left(\frac{d\bar{y}_{CG}}{dm}\right)\Delta m$$

$$\bar{z}_{CG} = \bar{z}_{CG_0} - \left(\frac{d\bar{z}_{CG}}{dm}\right)\Delta m$$

WHERE:

1) I_m = INTEGRATED TOTAL IMPULSE OF MAIN ENGINE.
2) T_m = MAIN ENGINE THRUST.
3) I_j = INTEGRATED TOTAL IMPULSE OF REACTION JETS.
4) ΣT_j = SUM TOTAL OF REACTION JET THRUSTS.
5) Δm_m = MAIN ENGINE PROPELLENT BURNED (MASS).
6) C_m = EXHAUST GAS VELOCITY OF MAIN ENGINE.
7) Δm_j = REACTION JET PROPELLENT BURNED (MASS).
8) C_j = EXHAUST GAS VELOCITY OF REACTION JET.
9) $\dot{m}_m$ = TIME RATE OF CHANGE OF MAIN ENGINE PROPELLENT MASS.
10) $\dot{m}_j$ = TIME RATE OF CHANGE OF REACTION JET PROPELLENT MASS.
11) $\dot{m}$ = TIME RATE OF CHANGE OF VEHICLE MASS.
12) m = MASS OF VEHICLE.
13) m_o = INITIAL MASS OF VEHICLE.
14) Δm = MAIN ENGINE PLUS REACTION JET PROPELLENT MASS BURNED.
15) $\bar{x}_{CG}$ = x-AXIS DISTANCE BETWEEN C.G. AND FIXED REFERENCE POINT.
16) $\bar{x}_{CG_0}$ = INITIAL VALUE OF $\bar{x}_{CG}$.
17) $d\bar{x}_{CG}/dm$ = DERIVATIVE OF $\bar{x}_{CG}$ WITH RESPECT TO PROPELLENT MASS
18) $\bar{y}_{CG}$ = y-AXIS DISTANCE BETWEEN C.G. AND FIXED REFERENCE POINT.
19) $\bar{y}_{CG_0}$ = INITIAL VALUE OF $\bar{y}_{CG}$.
20) $d\bar{y}_{CG}/dm$ = DERIVATIVE OF $\bar{y}_{CG}$ WITH RESPECT TO PROPELLENT MASS.
21) $\bar{z}_{CG}$ = z-AXIS DISTANCE BETWEEN C.G. AND FIXED REFERENCE POINT.
22) $\bar{z}_{CG_0}$ = INITIAL VALUE OF $\bar{z}_{CG}$
23) $d\bar{z}_{CG}/dm$ = DERIVATIVE OF $\bar{z}_{CG}$ WITH RESPECT TO PROPELLENT MASS.

IX. MOMENT AND PRODUCT OF INERTIA EQUATIONS

$$I_{xx} = I_{xx_0} - \left(\frac{dI_{xx}}{dm}\right)\Delta m$$

$$I_{yy} = I_{yy_0} - \left(\frac{dI_{yy}}{dm}\right)\Delta m$$

EQUATION SUMMARY FOR HOVER AND LANDING SIMULATION CONTINUED

IX. MOMENT AND PRODUCT OF INERTIA EQUATIONS CONTINUED

$$I_{zz} = I_{zz_0} - \left(\frac{dI_{zz}}{dm}\right)\Delta m$$

$$I_{xy} = \overline{I_{xy}}$$

$$I_{xz} = I_{xz_0} - \left(\frac{dI_{xz}}{dm}\right)\Delta m$$

$$I_{yz} = \overline{I_{yz}}$$

WHERE:
1) Δm = MAIN ENGINE PLUS REACTION JET PROPELLENT MASS BURNED.
2) I_{xx} = MOMENT OF INERTIA ABOUT BODY x-AXIS.
3) I_{xx_0} = INITIAL VALUE OF I_{xx}.
4) dI_{xx}/dm = DERIVATIVE OF I_{xx} WITH RESPECT TO PROPELLENT MASS.
5) I_{yy} = MOMENT OF INERTIA ABOUT BODY y-AXIS.
6) I_{yy_0} = INITIAL VALUE OF I_{yy}.
7) dI_{yy}/dm = DERIVATIVE OF I_{yy} WITH RESPECT TO PROPELLENT MASS.
8) I_{zz} = MOMENT OF INERTIA ABOUT BODY z-AXIS.
9) I_{zz_0} = INITIAL VALUE OF I_{zz}
10) dI_{zz}/dm = DERIVATIVE OF I_{zz} WITH RESPECT TO PROPELLENT MASS.
11) I_{xy} = PRODUCT OF INERTIA ABOUT BODY x-y AXES.
12) $\overline{I_{xy}}$ = AVERAGE VALUE OF I_{xy}
13) I_{xz} = PRODUCT OF INERTIA ABOUT BODY x-z AXES.
14) I_{xz_0} = INITIAL VALUE OF I_{xz}.
15) dI_{xz}/dm = DERIVATIVE OF I_{xz} WITH RESPECT TO PROPELLENT MASS.
16) I_{yz} = PRODUCT OF INERTIA ABOUT BODY y-z AXES.
17) $\overline{I_{yz}}$ = AVERAGE VALUE OF I_{yz}.

X. RANGE, LINE OF SIGHT AND GROUND TRACK CALCULATIONS

$$\left.\begin{aligned} R_X &= R_{X_0} + \int_0^t V_X\,dt \\ R_Y &= R_{Y_0} - \int_0^t V_Y\,dt \\ R_Z &= R_{Z_0} - \int_0^t V_Z\,dt. \end{aligned}\right\}$$

NOTE: UPPER LIMIT OF INTEGRAL SIGNIFIES THAT QUANTITY IS INTEGRATED OVER ENTIRE LENGTH OF COMPUTER RUN.

X. RANGE, LINE OF SIGHT AND GROUND TRACK CALCULATIONS CONTINUED

$$A = TAN^{-1}\left[\frac{R_Y}{R_Z}\right]$$

$$E = TAN^{-1}\left[\frac{R_X}{R_S}\right]$$

$$R_S = R_Z \cos A + R_Y \sin A$$

$$R_N = R_S\left[\frac{\sin A}{\cos A}\right]$$

$$R = R_X \sin E + R_S \cos E$$

$$\varepsilon_\phi = \phi + A$$

$$\dot{R}_N = V_Y \cos A - V_Z \sin A$$

$$\dot{R}_S = V_Z \cos A + V_Y \sin A$$

$$h = R_X - R_{Xg}$$

WHERE:

1) R_X = VEHICLE ALTITUDE (DEFINED BY C.G. POSITION)
2) R_Y = RANGE COMPONENT IN THE NEGATIVE INERTIAL Y DIRECTION.
3) R_Z = RANGE COMPONENT IN THE NEGATIVE INERTIAL Z DIRECTION
4) A = LINE OF SIGHT AZIMUTH ANGLE MEASURED FROM LANDING SITE.
5) E = LINE OF SIGHT ELEVATION ANGLE MEASURED WITH RESPECT TO SITE.
6) R_S = RANGE ALONG LUNAR SURFACE FROM LANDING SITE.
7) R_N = RANGE NORMAL TO R_S MEASURED IN THE GROUND PLANE.
8) R = LINE OF SIGHT RANGE FROM LUNAR LANDING SITE.
9) ε_ϕ = VEHICLE HEADING ANGLE ($\measuredangle$ BETWEEN z-BODY AXIS AND LOS).
10) $\dot{R}_N$ = RANGE RATE NORMAL TO LINE OF SIGHT.
11) $\dot{R}_S$ = RANGE RATE ALONG LUNAR SURFACE IN LINE OF SIGHT PLANE.
12) h = ALTITUDE OF LOWEST POINT OF LEM ABOVE LUNAR SURFACE.
13) R_{X_0} = INITIAL VALUE OF R_X
14) R_{Y_0} = INITIAL VALUE OF R_Y

EQUATION SUMMARY FOR HOVER AND LANDING SIMULATION CONTINUED

X. RANGE, LINE OF SIGHT AND GROUND TRACK CALCULATION EQUATIONS CONTINUED

15) R_{Z_0} = INITIAL VALUE OF R_Z.
16) V_X = VELOCITY IN INERTIAL X-DIRECTION.
17) V_Y = VELOCITY IN INERTIAL Y-DIRECTION.
18) V_Z = VELOCITY IN INERTIAL Z-DIRECTION.
19) ϕ = EULER ROLL ANGLE.
20) $\tan^{-1}$ = THE ANGLE WHOSE TANGENT IS.
21) R_{x_g} = DISTANCE OF C.G. ABOVE GROUND AT TOUCH DOWN.

XI. MOTION SEAT AND VISUAL DISPLAY EQUATIONS

$$\alpha_1' = -\frac{l_5 \psi}{2}$$

$$\alpha_2' = +\frac{l_5 \psi}{2}$$

$$\alpha_3' = -l_4 \theta$$

ALTITUDE =

LATERAL TRANSLATION =

LONGITUDINAL TRANSLATION =

ROLL ATTITUDE =

WHERE: 1) α_1' = RIGHT FRONT POST DISPLACEMENT FOR POSITIVE ANGLE
2) α_2' = LEFT FRONT POST DISPLACEMENT FOR POSITIVE ANGLE
3) α_3 = REAR POST DISPLACEMENT FOR POSITIVE ANGLE
4) ψ = YAW ANGLE SUPPLIED IN DEGREES
5) θ = PITCH ANGLE SUPPLIED IN DEGREES
6) l_4 = CONVERSION FACTOR FOR MOTION DEVICE DRIVE
7) l_5 = CONVERSION FACTOR FOR MOTION DEVICE DRIVE

APPENDIX NO. II

DEFINITION OF CONSTANT AND VARIABLE QUANTITIES

SUMMARY OF CONSTANT AND VARIABLE QUANTITIES FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

CONSTANT QUANTITIES ☑ VARIABLE QUANTITIES ☐

SYMBOL	DESCRIPTION	UNITS
g	LUNAR ACCELERATION OF GRAVITY	FT/SEC^2
I_{xy}	PRODUCT OF INERTIA ABOUT BODY x-y AXES	$SLUG\text{-}FT^2$
I_{yz}	PRODUCT OF INERTIA ABOUT BODY y-z AXES	$SLUG\text{-}FT^2$
l_D	CHARACTERISTIC DISTANCE FOR JET DAMPING ($l_{D_2} - l_{D_1}$ IN FIGURE 3)	FT
l_{DP}	CHARACTERISTIC DISTANCE FOR JET DAMPING (SEE FIGURE 4)	FT
$l_{D_{f_r}}^2$	CHARACTERISTIC DISTANCE SQUARED FOR JET DAMPING ($l_{D_2}^2 - l_{D_1}^2$ IN FIGURE 3)	FT^2
$\overline{I_{xy}}$	AVERAGE VALUE FOR PRODUCT OF INERTIA ABOUT BODY x-z AXES	$SLUG\text{-}FT^2$
I_{xz_0}	INITIAL VALUE FOR PRODUCT OF INERTIA ABOUT BODY x-z AXES	$SLUG\text{-}FT^2$
$\overline{I_{yz}}$	AVERAGE VALUE FOR PRODUCT OF INERTIA ABOUT BODY y-z AXES	$SLUG\text{-}FT^2$
dI_{xx}/dm	DERIVATIVE OF MOMENT OF INERTIA ABOUT BODY x-AXIS WITH RESPECT TO PROPELLENT MASS.	FT^2
dI_{yy}/dm	DERIVATIVE OF MOMENT OF INERTIA ABOUT BODY y-AXIS WITH RESPECT TO PROPELLENT MASS	FT^2
dI_{zz}/dm	DERIVATIVE OF MOMENT OF INERTIA ABOUT BODY z-AXIS WITH RESPECT TO PROPELLENT MASS	FT^2
dI_{xz}/dm	DERIVATIVE OF PRODUCT OF INERTIA ABOUT BODY x-z AXES WITH RESPECT TO PROPELLENT MASS.	FT^2
$d\bar{x}_{CG}/dm$	DERIVATIVE OF x-AXIS DISTANCE BETWEEN C.G. AND FIXED REFERENCE POINT WITH RESPECT TO PROPELLENT MASS	FT/SLUG
$d\bar{y}_{CG}/dm$	DERIVATIVE OF y-AXIS DISTANCE BETWEEN C.G. AND FIXED REFERENCE POINT WITH RESPECT TO PROPELLENT MASS	FT/SLUG
$d\bar{z}_{CG}/dm$	DERIVATIVE OF z-AXIS DISTANCE BETWEEN C.G. AND FIXED REFERENCE POINT WITH RESPECT TO PROPELLENT MASS	FT/SLUG
x_{Tm}	x-AXIS DISTANCE BETWEEN FIXED REFERENCE POINT AND MAIN ENGINE GIMBAL AXIS POINT	FT

SUMMARY OF CONSTANT AND VARIABLE QUANTITIES FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

CONSTANT QUANTITIES ☑ VARIABLE QUANTITIES ☐

SYMBOL	DESCRIPTION	UNITS
y_{Tm}	y-AXIS DISTANCE BETWEEN FIXED REFERENCE POINT AND MAIN ENGINE GIMBAL AXIS POINT	FT
z_{Tm}	z-AXIS DISTANCE BETWEEN FIXED REFERENCE POINT AND MAIN ENGINE GIMBAL AXIS POINT	FT
C_m	EXHAUST GAS VELOCITY OF MAIN ENGINE	FT/SEC
C_j	EXHAUST GAS VELOCITY OF REACTION JET	FT/SEC
m_o	INITIAL MASS OF VEHICLE	SLUGS
I_{xx_o}	INITIAL VALUE FOR MOMENT OF INERTIA ABOUT BODY x-AXIS	SLUG-FT^2
I_{yy_o}	INITIAL VALUE FOR MOMENT OF INERTIA ABOUT BODY y-AXIS	SLUG-FT^2
I_{zz_o}	INITIAL VALUE FOR MOMENT OF INERTIA ABOUT BODY z-AXIS	SLUG-FT^2
$\bar{x}_{CG_o}$	INITIAL VALUE FOR x-AXIS DISTANCE BETWEEN C.G. AND FIXED REFERENCE POINT	FT
$\bar{y}_{CG_o}$	INITIAL VALUE FOR y-AXIS DISTANCE BETWEEN C.G. AND FIXED REFERENCE POINT	FT
$\bar{z}_{CG_o}$	INITIAL VALUE FOR z-AXIS DISTANCE BETWEEN C.G. AND FIXED REFERENCE POINT	FT
θ_o	INITIAL VALUE FOR EULER PITCH ANGLE	DEG
ψ_o	INITIAL VALUE FOR EULER YAW ANGLE	DEG
ϕ_o	INITIAL VALUE FOR EULER ROLL ANGLE	DEG
R_{X_o}	INITIAL VALUE FOR VEHICLE ALTITUDE (REF. TO C.G.)	FT
R_{Y_o}	INITIAL VALUE FOR RANGE COMPONENT IN THE NEGATIVE INERTIAL Y-AXIS DIRECTION	FT
R_{Z_o}	INITIAL VALUE FOR RANGE COMPONENT IN THE NEGATIVE INERTIAL Z-AXIS DIRECTION	FT

SUMMARY OF CONSTANT AND VARIABLE QUANTITIES
FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

CONSTANT QUANTITIES ☑ VARIABLE QUANTITIES ☐

SYMBOL	DESCRIPTION	UNITS
u_o	INITIAL VALUE FOR VEHICLE VELOCITY ALONG BODY x-AXIS	FT/SEC
v_o	INITIAL VALUE FOR VEHICLE VELOCITY ALONG BODY y-AXIS	FT/SEC
w_o	INITIAL VALUE FOR VEHICLE VELOCITY ALONG BODY z-AXIS	FT/SEC
p_o	INITIAL VALUE FOR ANGULAR VELOCITY ABOUT BODY x-AXIS	RAD/SEC
q_o	INITIAL VALUE FOR ANGULAR VELOCITY ABOUT BODY y-AXIS	RAD/SEC
r_o	INITIAL VALUE FOR ANGULAR VELOCITY ABOUT BODY z-AXIS	RAD/SEC
Δm_{m_T}	MAXIMUM MAIN ENGINE PROPELLENT MASS	SLUGS
Δm_{j_T}	MAXIMUM REACTION JET PROPELLENT MASS	SLUGS
R_{x_g}	x-AXIS DISTANCE BETWEEN C.G. AT TOUCHDOWN AND LANDING GEAR FEET	FT
x_j	x-AXIS DISTANCE BETWEEN TOUCHDOWN C.G. AND PLANE OF REACTION JETS. (SEE FIGURE 7)	FT
l_{jp}	1/2 ROLL JET COUPLE MOMENT ARM	FT
l_{jq}	1/2 PITCH JET COUPLE MOMENT ARM	FT
l_{jr}	1/2 YAW JET COUPLE MAMENT ARM	FT
l_4	MOTION SEAT SCALE FACTOR	IN/RAD
l_5	MOTION SEAT SCALE FACTOR	IN/RAD

SUMMARY OF CONSTANT AND VARIABLE QUANTITIES FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

CONSTANT QUANTITIES ☐ VARIABLE QUANTITIES ☑

SYMBOL	DESCRIPTION	UNITS
m	MASS OF VEHICLE	SLUGS
$\dot{u}$	VEHICLE ACCELERATION ALONG BODY x-AXIS	FT/SEC^2
u	VEHICLE VELOCITY ALONG BODY x-AXIS	FT/SEC
$\dot{v}$	VEHICLE ACCELERATION ALONG BODY y-AXIS	FT/SEC^2
v	VEHICLE VELOCITY ALONG BODY y-AXIS	FT/SEC
$\dot{w}$	VEHICLE ACCELERATION ALONG BODY z-AXIS	FT/SEC^2
w	VEHICLE VELOCITY ALONG BODY z-AXIS	FT/SEC
$\dot{p}$	ANGULAR ACCELERATION ABOUT BODY x-AXIS	RAD/SEC^2
p	ANGULAR VELOCITY ABOUT BODY x-AXIS	RAD/SEC
$\dot{q}$	ANGULAR ACCELERATION ABOUT BODY y-AXIS	RAD/SEC^2
q	ANGULAR VELOCITY ABOUT BODY y-AXIS	RAD/SEC
$\dot{r}$	ANGULAR ACCELERATION ABOUT BODY z-AXIS	RAD/SEC^2
r	ANGULAR VELOCITY ABOUT BODY z-AXIS	RAD/SEC
I_{xx}	MOMENT OF INERTIA ABOUT BODY x-AXIS	$SLUG\text{-}FT^2$
I_{yy}	MOMENT OF INERTIA ABOUT BODY y-AXIS	$SLUG\text{-}FT^2$
I_{zz}	MOMENT OF INERTIA ABOUT BODY z-AXIS	$SLUG\text{-}FT^2$
I_{xz}	PRODUCT OF INERTIA ABOUT BODY x-z AXES	$SLUG\text{-}FT^2$

[redacted]

SUMMARY OF CONSTANT AND VARIABLE QUANTITIES FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

CONSTANT QUANTITIES ☐ VARIABLE QUANTITIES ☑

SYMBOL	DESCRIPTION	UNITS
$\dot{m}$	TIME RATE OF CHANGE FOR VEHICLE MASS	SLUGS/SEC
B_x	SUM OF THRUST FORCES IN THE BODY x-AXIS DIRECTION	POUNDS
B_y	SUM OF THRUST FORCES IN THE BODY y-AXIS DIRECTION	POUNDS
B_z	SUM OF THRUST FORCES IN THE BODY z-AXIS DIRECTION	POUNDS
L	SUM OF THRUST MOMENTS ABOUT BODY x-AXIS	FT. POUNDS
M	SUM OF THRUST MOMENTS ABOUT BODY y-AXIS	FT. POUNDS
N	SUM OF THRUST MOMENTS ABOUT BODY z-AXIS	FT. POUNDS
l_1, l_2, l_3 m_1, m_2, m_3 n_1, n_2, n_3	DIRECTION COSINES	—
V_x	VELOCITY IN INERTIAL X-DIRECTION	FT/SEC
V_y	VELOCITY IN INERTIAL Y-DIRECTION	FT/SEC
V_z	VELOCITY IN INERTIAL Z-DIRECTION	FT/SEC
$\dot{\phi}$	ANGULAR RATE FOR EULER ROLL ANGLE	RAD/SEC
$\dot{\psi}$	ANGULAR RATE FOR EULER YAW ANGLE	RAD/SEC
$\dot{\theta}$	ANGULAR RATE FOR EULER PITCH ANGLE	RAD/SEC
ϕ	EULER ROLL ANGLE	DEG
ψ	EULER YAW ANGLE	DEG
θ	EULER PITCH ANGLE	DEG

[redacted]

SUMMARY OF CONSTANT AND VARIABLE QUANTITIES FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

CONSTANT QUANTITIES ☐ VARIABLE QUANTITIES ☑

SYMBOL	DESCRIPTION	UNITS
Δm	MAIN ENGINE PLUS REACTION JET PROPELLENT MASS BURNED	SLUGS
$\dot{m}_m$	TIME RATE OF CHANGE OF MAIN ENGINE PROPELLENT MASS	SLUGS/SEC
$\dot{m}_j$	TIME RATE OF CHANGE FOR REACTION JET PROPELLENT MASS	SLUGS/SEC
T_m	MAIN ENGINE THRUST LEVEL	POUNDS
T_{jx}	SUM OF X-AXIS REACTION JET THRUST COMPONENTS	POUNDS
T_{jy}	SUM OF Y-AXIS REACTION JET THRUST COMPONENTS	POUNDS
T_{jz}	SUM OF Z-AXIS REACTION JET THRUST COMPONENTS	POUNDS
$\delta_{\theta m}$	MAIN ENGINE GIMBAL ANGLE ABOUT BODY Y-AXIS	DEG
$\delta_{\psi m}$	MAIN ENGINE GIMBAL ANGLE ABOUT BODY Z-AXIS	DEG
x_m	X-AXIS DISTANCE BETWEEN C.G. AND MAIN ENGINE GIMBAL AXIS POINT	FT
y_m	Y-AXIS DISTANCE BETWEEN C.G. AND MAIN ENGINE GIMBAL AXIS POINT	FT
z_m	Z-AXIS DISTANCE BETWEEN C.G. AND MAIN ENGINE GIMBAL AXIS POINT	FT
$\bar{x}_{CG}$	X-AXIS DISTANCE BETWEEN C.G. AND FIXED REFERENCE POINT	FT
$\bar{y}_{CG}$	Y-AXIS DISTANCE BETWEEN C.G. AND FIXED REFERENCE POINT	FT
$\bar{z}_{CG}$	Z-AXIS DISTANCE BETWEEN C.G. AND FIXED REFERENCE POINT	FT
I_m	INTEGRATED TOTAL IMPULSE OF MAIN ENGINE	POUND-SEC
I_j	INTEGRATED TOTAL IMPULSE OF REACTION JETS	POUND-SEC

SUMMARY OF CONSTANT AND VARIABLE QUANTITIES FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

CONSTANT QUANTITIES ☐ VARIABLE QUANTITIES ☑

SYMBOL	DESCRIPTION	UNITS
ΣT_j	SUM TOTAL OF REACTION JET THRUSTS	POUNDS
Δm_m	MAIN ENGINE PROPELLENT BURNED (MASS)	SLUGS
Δm_j	REACTION JET PROPELLENT BURNED (MASS)	SLUGS
R_x	VEHICLE ALTITUDE (REFERENCED TO C.G.)	FT
R_Y	RANGE COMPONENT IN THE NEGATIVE INERTIAL Y-AXIS DIRECTION	FT
R_Z	RANGE COMPONENT IN THE NEGATIVE INERTIAL Z-AXIS DIRECTION	FT
R_S	RANGE ALONG LUNAR SURFACE FROM LANDING SITE	FT
$R=\rho$	LINE OF SIGHT RANGE FROM LUNAR LANDING SITE.	FT
A	AZIMUTH DIRECTION ANGLE FOR LINE OF SIGHT FROM LANDING SITE	DEG
E	ELEVATION ANGLE FOR LINE OF SIGHT MEASURED WITH RESPECT TO RANGE ALONG LUNAR SURFACE (R_S).	DEG
R_N	RANGE NORMAL TO LINE OF SIGHT (SEE FIGURE 1)	FT
$\dot{R}_N$	RANGE RATE NORMAL TO LINE OF SIGHT	FT/SEC
$\dot{R}_S$	RANGE RATE ALONG LUNAR SURFACE IN LINE OF SIGHT PLANE	FT/SEC
ε_ϕ	HEADING ERROR $(\phi + A)$	DEG
L_j	SUM OF REACTION JET THRUST MOMENTS ABOUT BODY x-AXIS	FT.-POUNDS
M_j	SUM OF REACTION JET THRUST MOMENTS ABOUT BODY y-AXIS	FT.-POUNDS
N_j	SUM OF REACTION JET THRUST MOMENTS ABOUT BODY z-AXIS	FT.-POUNDS

SUMMARY OF CONSTANT AND VARIABLE QUANTITIES
FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

CONSTANT QUANTITIES ☐ VARIABLE QUANTITIES ☑

SYMBOL	DESCRIPTION	UNITS
h	ALTITUDE (REFERENCED TO LANDING GEAR FEET)	FT
T_{jp}	SUM THRUST OF ROLL REACTION JET PAIR	POUNDS
T_{jq}	SUM THRUST OF PITCH REACTION JET PAIR	POUNDS
T_{jr}	SUM THRUST OF YAW REACTION JET PAIR	POUNDS
I_{jx}	INTEGRATED TOTAL IMPULSE OF x-AXIS TRANSLATION JETS	POUND-SEC
I_{jy}	INTEGRATED TOTAL IMPULSE OF y-AXIS TRANSLATION JETS	POUND-SEC
I_{jz}	INTEGRATED TOTAL IMPULSE OF z-AXIS TRANSLATION JETS	POUND-SEC
I_{jp}	INTEGRATED TOTAL IMPULSE OF ROLL JETS	POUND-SEC
I_{jq}	INTEGRATED TOTAL IMPULSE OF PITCH JETS	POUND-SEC
I_{jr}	INTEGRATED TOTAL IMPULSE OF YAW JETS	POUND-SEC

APPENDIX NO. III

DEFINITIONS OF LEM GEOMETRY AND SCHEMATIC COMPUTER FLOW CHART

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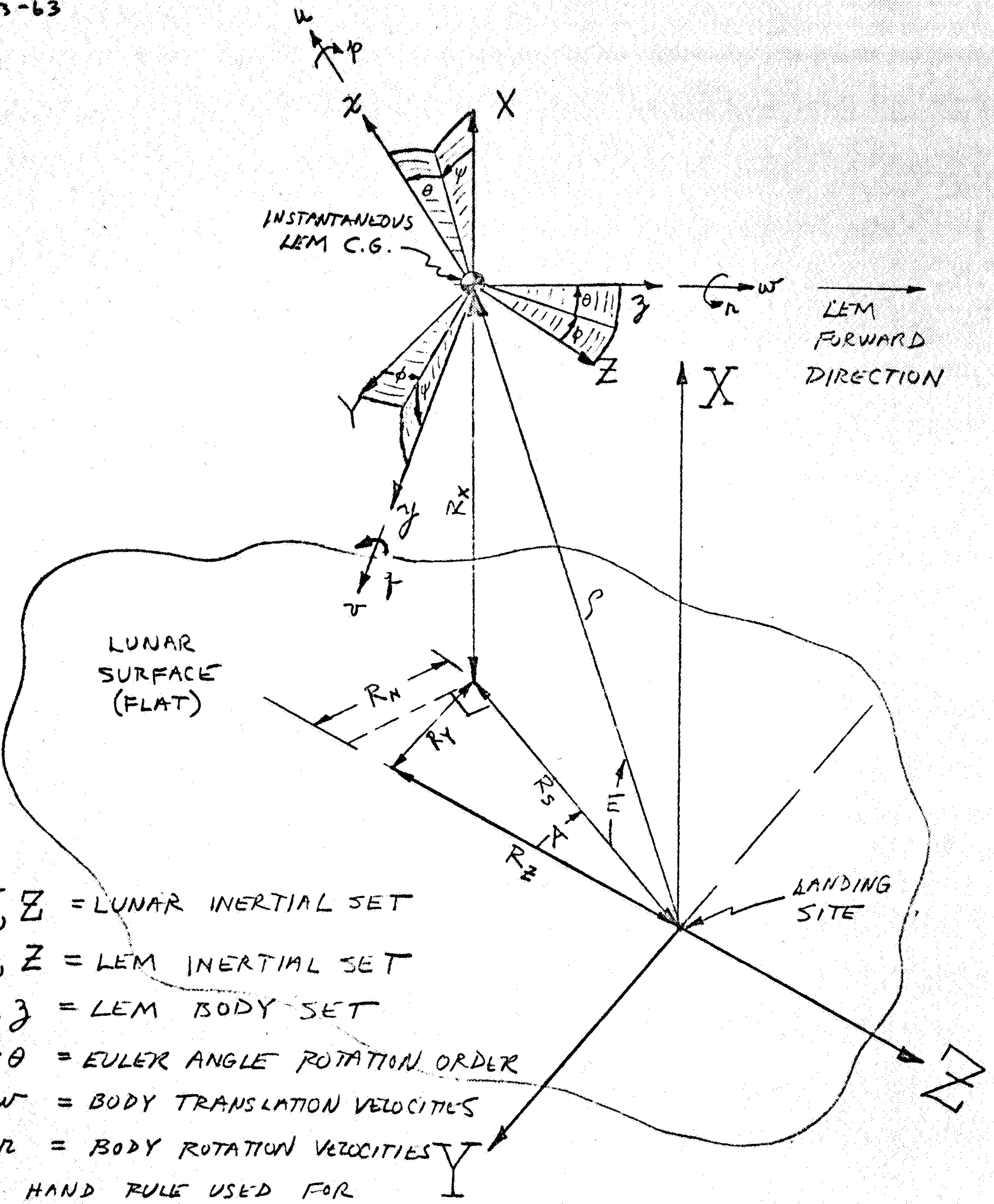
PLM 1-22-63
Rev. 2-1-63
Rev. 2-13-63



X, Y, Z = LUNAR INERTIAL SET
X, Y, Z = LEM INERTIAL SET
x, y, z = LEM BODY SET
$\phi \rightarrow \psi \rightarrow \theta$ = EULER ANGLE ROTATION ORDER
u, v, w = BODY TRANSLATION VELOCITIES
p, q, r = BODY ROTATION VELOCITIES
(RIGHT HAND RULE USED FOR
+ ROTATIONS ABOUT AXES)
NOTE: PREVIOUS SYMBOL FOR "ρ" WAS "R"

FIG. 1
LEM REFERENCE AXES SYSTEM
FOR LUNAR LANDING SIMULATION

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PLM 1-22-63

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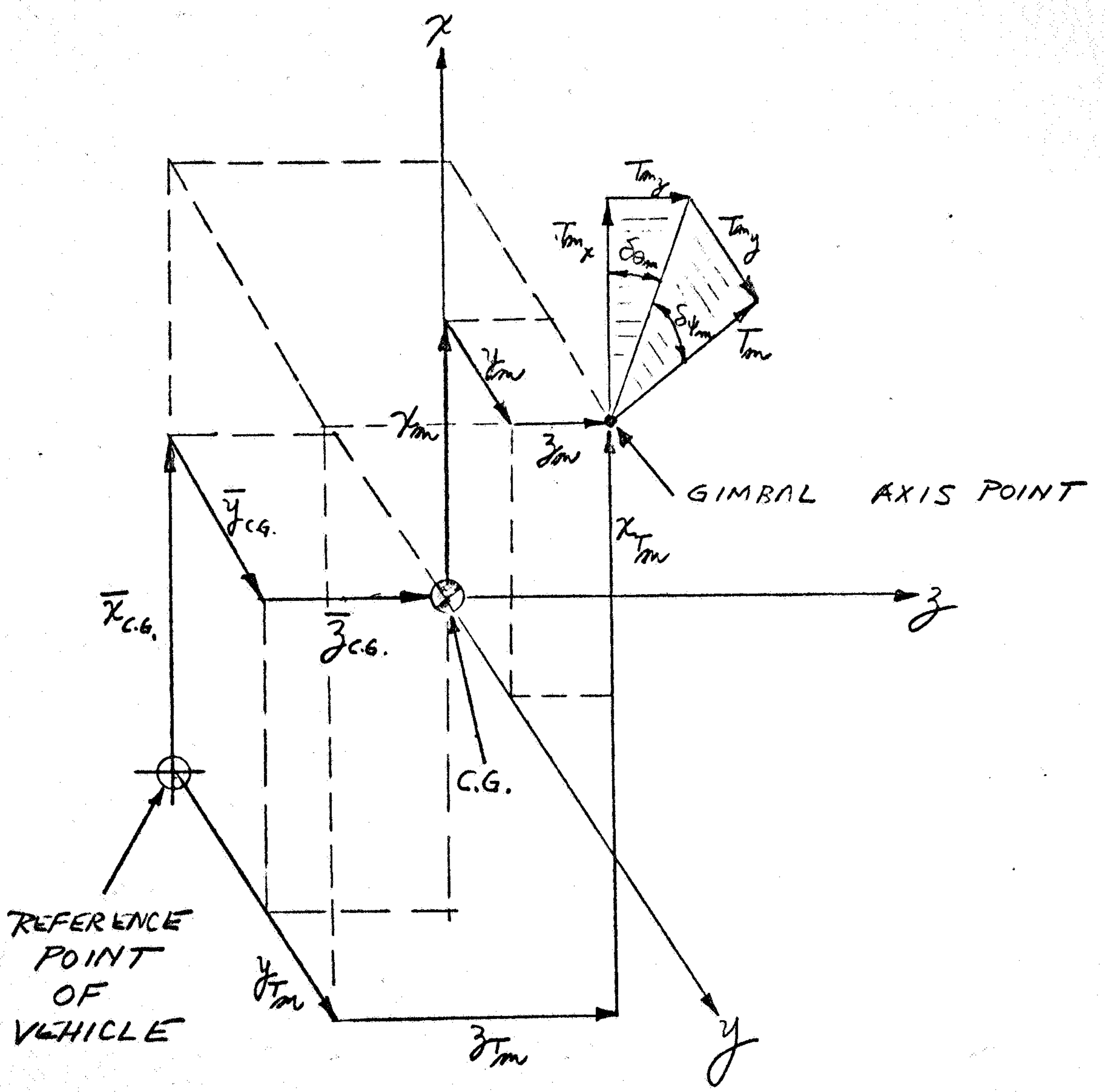

NOTE: SUBSCRIPT "m" REFERS TO MAIN (DESCENT) ENGINE

FIG. 2.
LEM THRUST VECTOR AND C.G. SHIFT GEOMETRY FOR MAIN (DESCENT) ENGINE

REPORT: LED570-1
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[redacted]

PLM 2-13-63 #1 of 2

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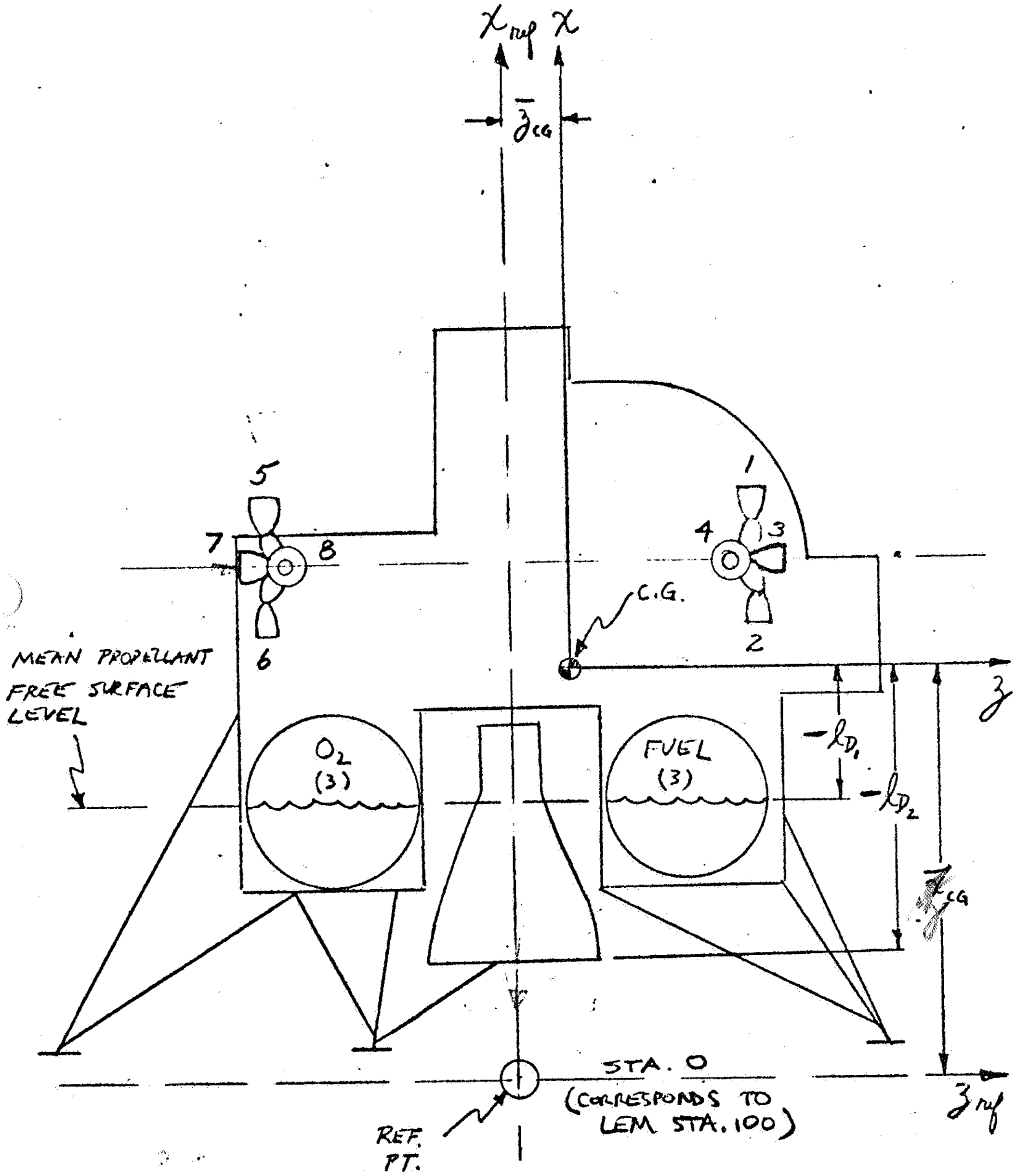

FIG. 3. LEM SIDE VIEW

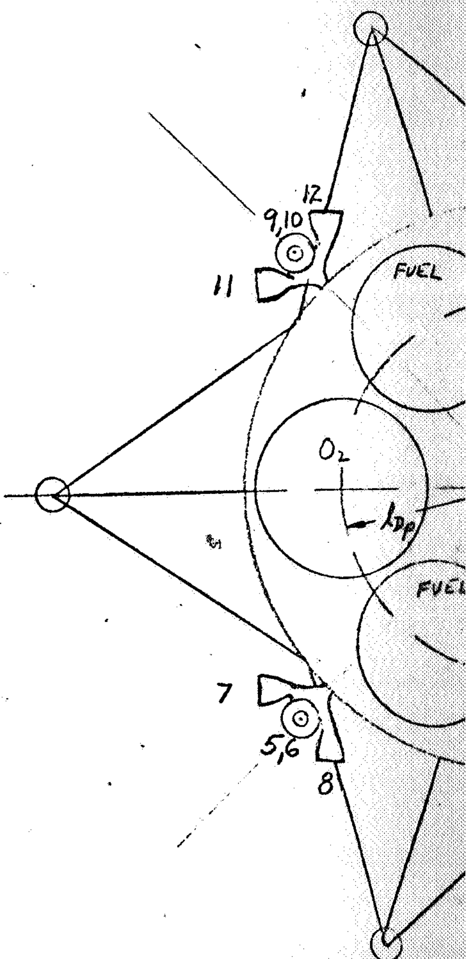

FIG. 4. LEM TO

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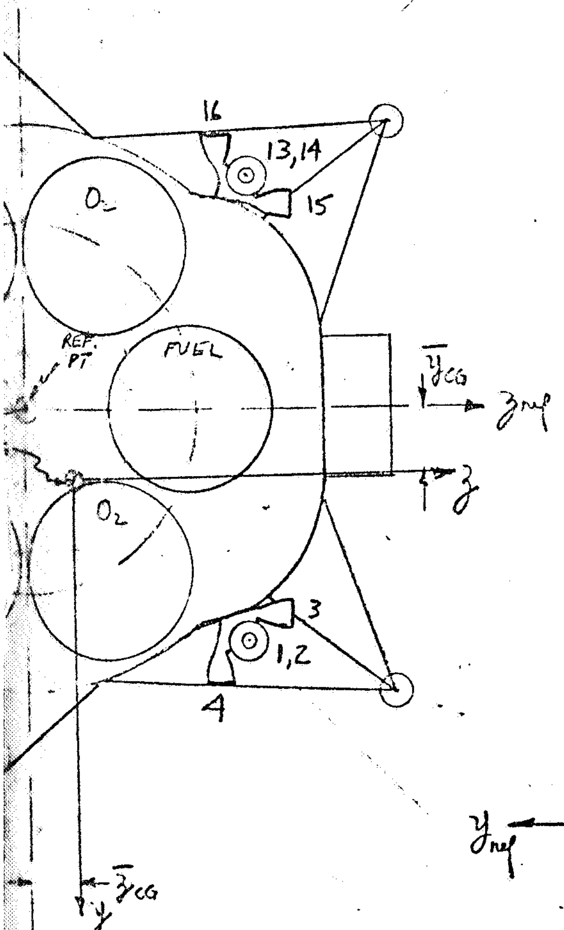

VIEW

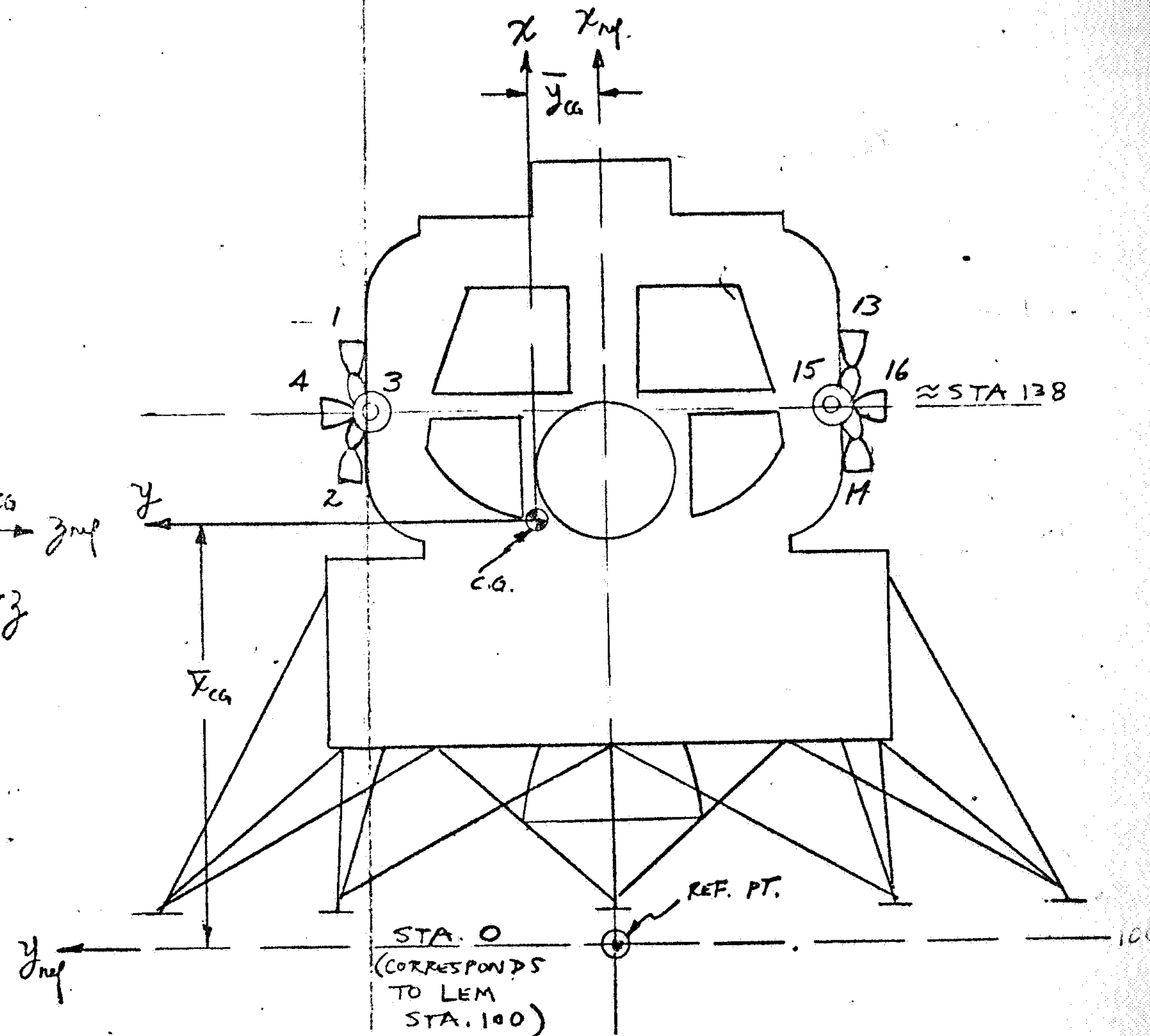

FIG. 5. LEM FRONT VIEW

PLM 1-21-63
Rev. 2-1-63
Rev 2-6-63
Rev 2-13-63

FIG. 6. LUNAR LANDING SIM

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BODY AXIS TRANSLATION

Inputs: u_0, v_0, w_0

$$B_x = m(\dot{u} - vr + wq) + mgl_1$$

$$B_y = m(\dot{v} - wp + ur) + mgm_1 - 2\dot{m}rl_D$$

$$B_z = m(\dot{w} - uq + vp) + mgn_1 + 2\dot{m}ql_D$$

Outputs: u, v, w; $\dot{u}, \dot{v}, \dot{w}$

Inputs: B_x, B_y, B_z | g | m | $\dot{m}$ | p, q, r | l_1, m_1, n_1 | l_D

DIRECTION COSINES (EULER ORDER: $\phi \to \psi \to \theta$)

$$l_1 = \cos\theta\cos\psi$$

$$m_1 = -\sin\psi$$

$$n_1 = \sin\theta\cos\psi$$

$$l_2 = \cos\theta\sin\psi\cos\phi + \sin\theta\sin\phi$$

$$m_2 = \cos\psi\cos\phi$$

$$n_2 = \sin\theta\sin\psi\cos\phi - \cos\theta\sin\phi$$

$$l_3 = \cos\theta\sin\psi\sin\phi - \sin\theta\cos\phi$$

$$m_3 = \cos\psi\sin\phi$$

$$n_3 = \sin\theta\sin\psi\sin\phi + \cos\theta\cos\phi$$

Outputs: l_1, l_2 … | m_1 … | n_1 …

Inputs: ϕ | ψ | θ

BODY AXIS ROTATION

Inputs: p_0, q_0, r_0

$$I_{xx}\dot{p} = -(I_{zz} - I_{yy})qr + I_{yz}(q^2 - r^2) + I_{xz}(\dot{r} + pq) + I_{xy}(\dot{q} - pr) + p\dot{m}l_{D_p}^2 + L$$

$$I_{yy}\dot{q} = -(I_{xx} - I_{zz})pr + I_{xz}(r^2 - p^2) + I_{xy}(\dot{p} + qr) + I_{yz}(\dot{r} - pq) + q\dot{m}l_{D_{qr}}^2 + M$$

$$I_{zz}\dot{r} = -(I_{yy} - I_{xx})pq + I_{xy}(p^2 - q^2) + I_{xz}(\dot{p} - qr) + I_{yz}(\dot{q} + pr) + r\dot{m}l_{D_{qr}}^2 + N$$

Outputs: $\dot{p}$ | $\dot{q}$ | $\dot{r}$

Inputs: I_{xx}, I_{yy}, I_{zz} | I_{xy}, I_{xz}, I_{yz} | l_{D_p} | $l_{D_{qr}}$ | L, M, N

EULER ANGLES AND RATES (ORDER: $\phi \to \psi \to \theta$)

Inputs: ϕ_0, ψ_0, θ_0

$$\dot{\phi} = [p\cos\theta + r\sin\theta]/\cos\psi$$

$$\dot{\psi} = r\cos\theta - p\sin\theta$$

$$\dot{\theta} = q + [\sin\psi][p\cos\theta + r\sin\theta]/\cos\psi$$

$$\phi = \phi_0 + \int_0^t \dot{\phi}\,dt$$

$$\psi = \psi_0 + \int_0^t \dot{\psi}\,dt$$

$$\theta = \theta_0 + \int_0^t \dot{\theta}\,dt$$

Inputs: p | q | r

INERTIAL TRANSLATION

$$V_X = l_1u + m_1v + n_1w$$

$$V_Y = l_2u + m_2v + n_2w$$

$$V_Z = l_3u + m_3v + n_3w$$

Outputs: V_X, V_Y, V_Z

Inputs: l_1, l_2, l_3 | m_1, m_2, m_3 | n_1, n_2, n_3 | u, v, w

BODY FORCES AND MOMENTS

$$B_x = T_m\cos\delta\theta_m\cos\delta\psi_m + T_{jx}$$

$$B_y = T_m\sin\delta\psi_m + T_{jy}$$

$$B_z = T_m\sin\delta\theta_m\cos\delta\psi_m + T_{jz}$$

$$L = T_m(y_m\sin\delta\theta_m\cos\delta\psi_m - z_m\sin\delta\psi_m) + L_j$$

$$M = T_m(z_m\cos\delta\theta_m\cos\delta\psi_m - x_m\sin\delta\theta_m\cos\delta\psi_m) + M_j$$

$$N = T_m(x_m\sin\delta\psi_m - y_m\cos\delta\theta_m\cos\delta\psi_m) + N_j$$

Inputs: x_m, y_m, z_m | T_m | T_{jx}, T_{jy}, T_{jz} | L_j, M_j, N_j | $\delta\theta_m$ | $\delta\psi_m$

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...ATOR AND EQUATIONS OF MOTION #2 of 2

NOTES: (1) SUBSCRIPT "m" REFERS TO MAIN (DESCENT) ENGINE
(2) SUBSCRIPT "j" REFERS TO REACTION CONTROL JETS
(3) SUPERSCRIPT "c" REFERS TO PILOT COMMAND
(4) SYMBOL "ρ" PREVIOUSLY WAS "R"

MASS AND C.G.

Inputs: m_0, $\bar{x}_{CG_0}$, $\bar{y}_{CG_0}$, $\bar{z}_{CG_0}$, $d\bar{x}_{CG}/dm$, $d\bar{y}_{CG}/dm$, $d\bar{z}_{CG}/dm$, C_m, C_j, T_m, ΣT_j, Δm_{m_T}, Δm_{j_T}

$$I_m = \int_0^t T_m\,dt$$
$$I_j = \int_0^t (\Sigma T_j)\,dt$$
$$\Delta m_m = I_m / C_m$$
$$\Delta m_j = I_j / C_j$$
$$\dot{m}_m = T_m / C_m$$
$$\dot{m}_j = (\Sigma T_j)/C_j$$
$$\dot{m} = -\dot{m}_m - \dot{m}_j$$
$$\Delta m = \Delta m_m + \Delta m_j$$
$$m = m_0 - \Delta m$$

NOTE: IF $\Delta m_m > \Delta m_{m_T}$ OR $\Delta m_j > \Delta m_{j_T}$, THEN RESET COMPUTER

$$\bar{x}_{CG} = \bar{x}_{CG_0} - (d\bar{x}_{CG}/dm)\Delta m$$
$$\bar{y}_{CG} = \bar{y}_{CG_0} - (d\bar{y}_{CG}/dm)\Delta m$$
$$\bar{z}_{CG} = \bar{z}_{CG_0} - (d\bar{z}_{CG}/dm)\Delta m$$

Outputs: I_m, I_j; Δm, Δm_m, Δm_j; $\dot{m}_m$, $\dot{m}_j$; $\dot{m}$; m; $\bar{x}_{CG}$, $\bar{y}_{CG}$, $\bar{z}_{CG}$

MOMENTS AND PRODUCTS OF INERTIA

$$I_{xx} = I_{xx_0} - \frac{dI_{xx}}{dm}\Delta m$$
$$I_{yy} = I_{yy_0} - \frac{dI_{yy}}{dm}\Delta m$$
$$I_{zz} = I_{zz_0} - \frac{dI_{zz}}{dm}\Delta m$$
$$I_{xy} = \overline{I_{xy}}$$
$$I_{xz} = I_{xz_0} - \frac{dI_{xz}}{dm}\Delta m$$
$$I_{yz} = \overline{I_{yz}}$$

Inputs: dI_{xx}/dm, dI_{yy}/dm, dI_{zz}/dm, Δm

Outputs: I_{xx}, I_{yy}, I_{zz}; I_{xy}, I_{xz}, I_{yz}

MAIN THRUST MOMENT ARMS

$$x_m = x_{T_m} - \bar{x}_{CG}$$
$$y_m = y_{T_m} - \bar{y}_{CG}$$
$$z_m = z_{T_m} - \bar{z}_{CG}$$

Inputs: $x_{T_m}, y_{T_m}, z_{T_m}$; $\bar{x}_{CG}, \bar{y}_{CG}, \bar{z}_{CG}$

Outputs: x_m, y_m, z_m

Left margin: $\dot{m}_3$, m_3, m_0, $\bar{x}_{CG_0}$, $\bar{y}_{CG_0}$, $\bar{z}_{CG_0}$, $\dot{\phi}$, $\dot{\psi}$, $\dot{\theta}$, B_y, B_z, M, N

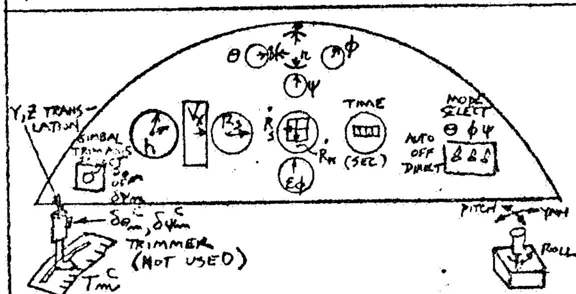
RANGE, LINE OF SIGHT, AND GROUND TRACK

Inputs: $R_{X_0}, R_{Y_0}, R_{Z_0}$; V_X, V_Y, V_Z, ϕ, R_{Xg}

$$R_X = R_{X_0} + \int_0^t V_X\,dt$$
$$R_Y = R_{Y_0} - \int_0^t V_Y\,dt$$
$$R_Z = R_{Z_0} - \int_0^t V_Z\,dt$$
$$A = \tan^{-1}[R_Y/R_Z]$$
$$R_S = R_Z \cos A + R_Y \sin A$$
$$R_N = R_S \sin A / \cos A$$
$$E = \tan^{-1}[R_X/R_S]$$
$$\rho = R_X \sin E + R_S \cos E$$
$$\varepsilon_\phi = \phi + A$$
$$\dot{R}_N = V_Y \cos A - V_Z \sin A$$
$$\dot{R}_S = V_Z \cos A + V_Y \sin A$$
$$h = R_X - R_{Xg}$$

Outputs: R_X, R_Y, R_Z, h; R_S, ρ, R_N; A, E; ε_ϕ; $\dot{R}_N, \dot{R}_S$

LANDING SIMULATION COCKPIT



Inputs: θ, ψ, ϕ; $\rho, \dot{\rho}, h$; ε_ϕ; $V_X, \dot{R}_N, \dot{R}_S$; h, R_S

Outputs: L_j^c, M_j^c, N_j^c *; $T_{jx}^c, T_{jy}^c, T_{jz}^c$ *; T_m^c; $\delta\theta_m^c, \delta\psi_m^c$

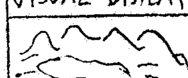
MOTION DRIVE

x_1', x_2', x_3'

Inputs: θ, ψ

Outputs: x_1', x_2', x_3'

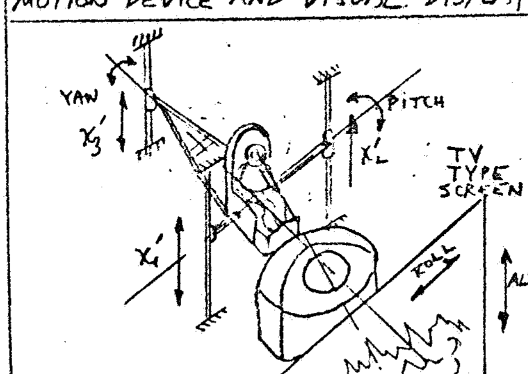
VISUAL DISPLAY



Inputs: ϕ, $\dot{\phi}$, R_X, V_Y, V_Z

Output: TV TYPE PICTURE

MOTION DEVICE AND VISUAL DISPLAY



Inputs: x_1', x_2', x_3'; TV TYPE PICTURE

MAIN (DESCENT) ENGINE GIMBAL SYSTEM

Input: $\delta\theta_m^c, \delta\psi_m^c$

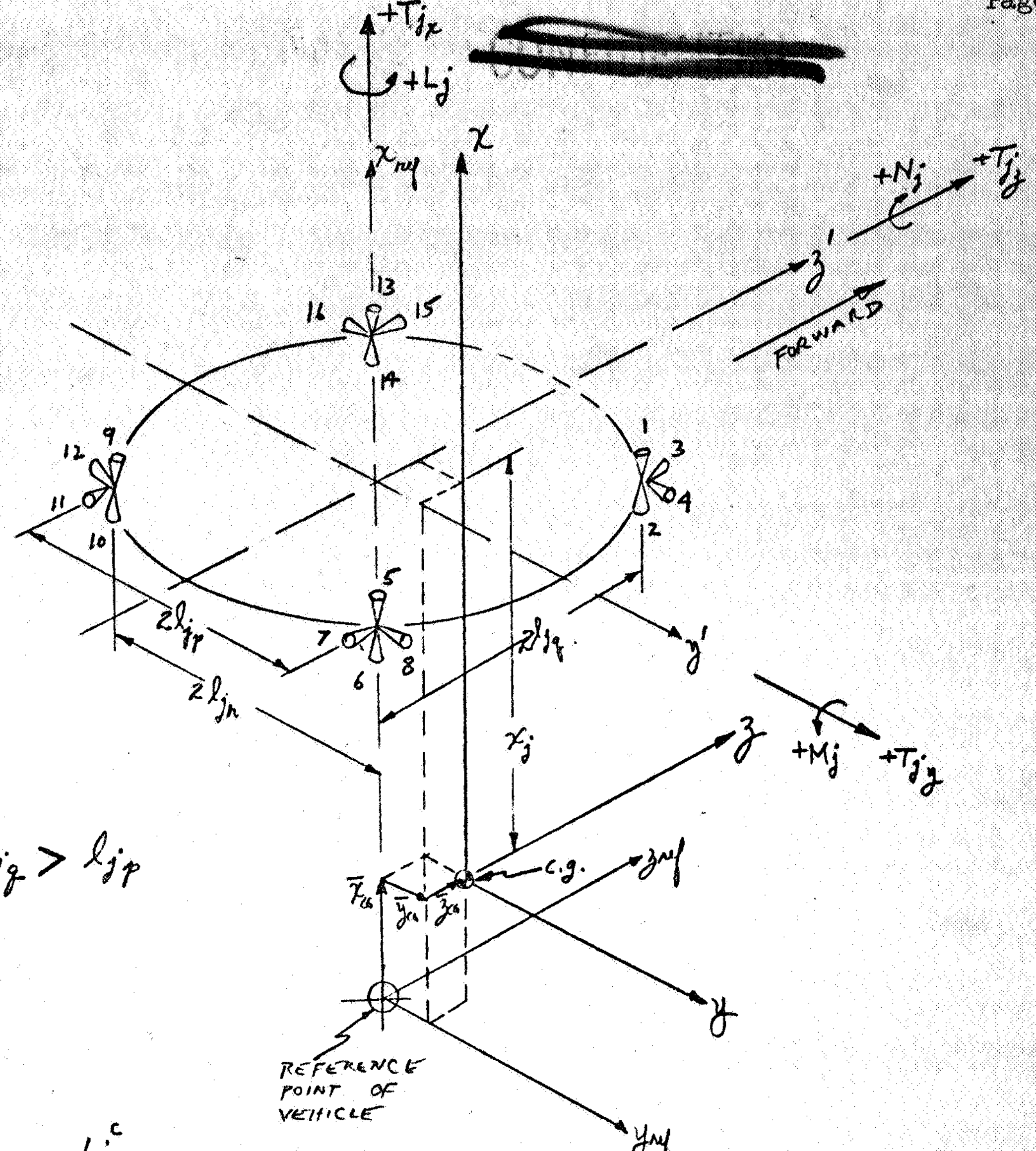
Output: $\delta\theta_m, \delta\psi_m$

MAIN (DESCENT) ENGINE

Input: T_m^c

Output: T_m

* SEE FIG. 7 FOR RCS EQUATIONS



NOTE: $l_{jn} = l_{jq} > l_{jp}$

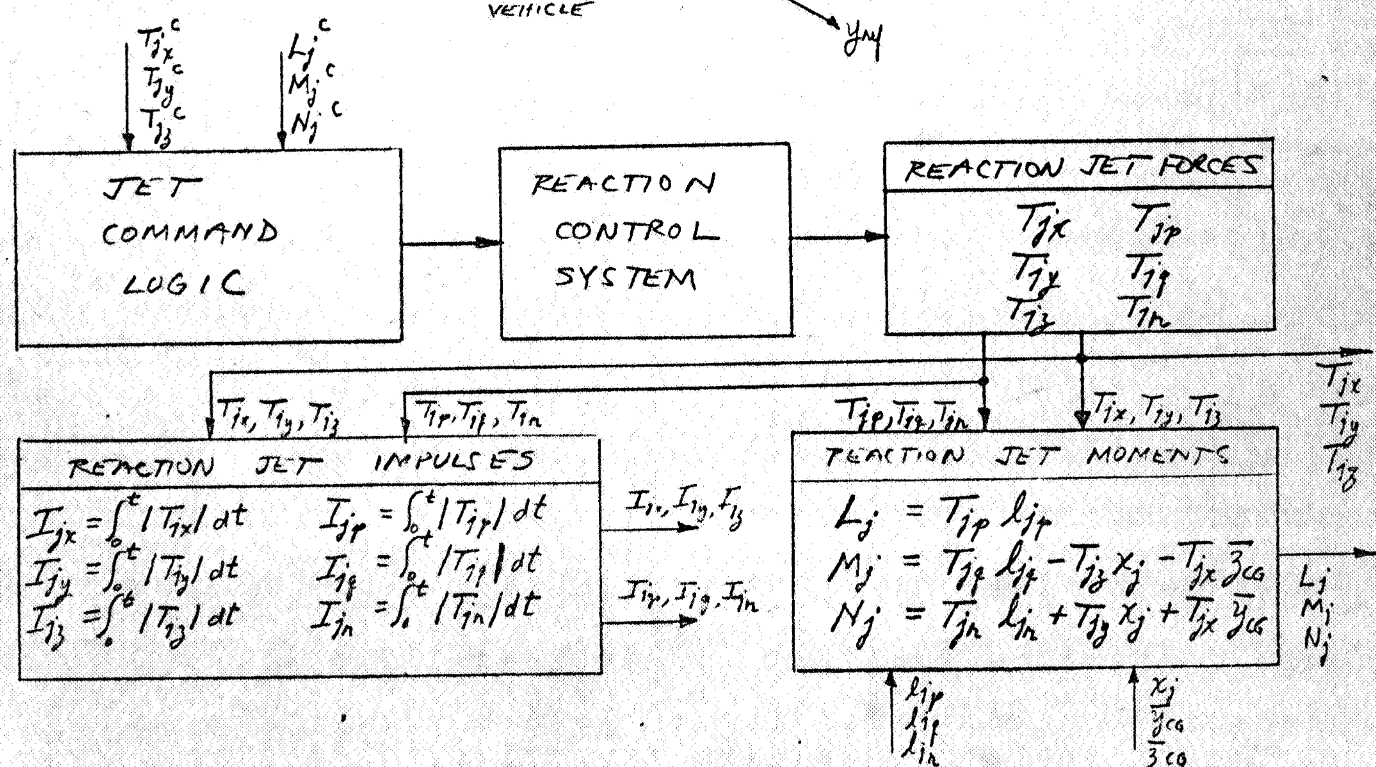


FIGURE 7. REACTION CONTROL SYSTEM EQUATIONS

APPENDIX NO. IV

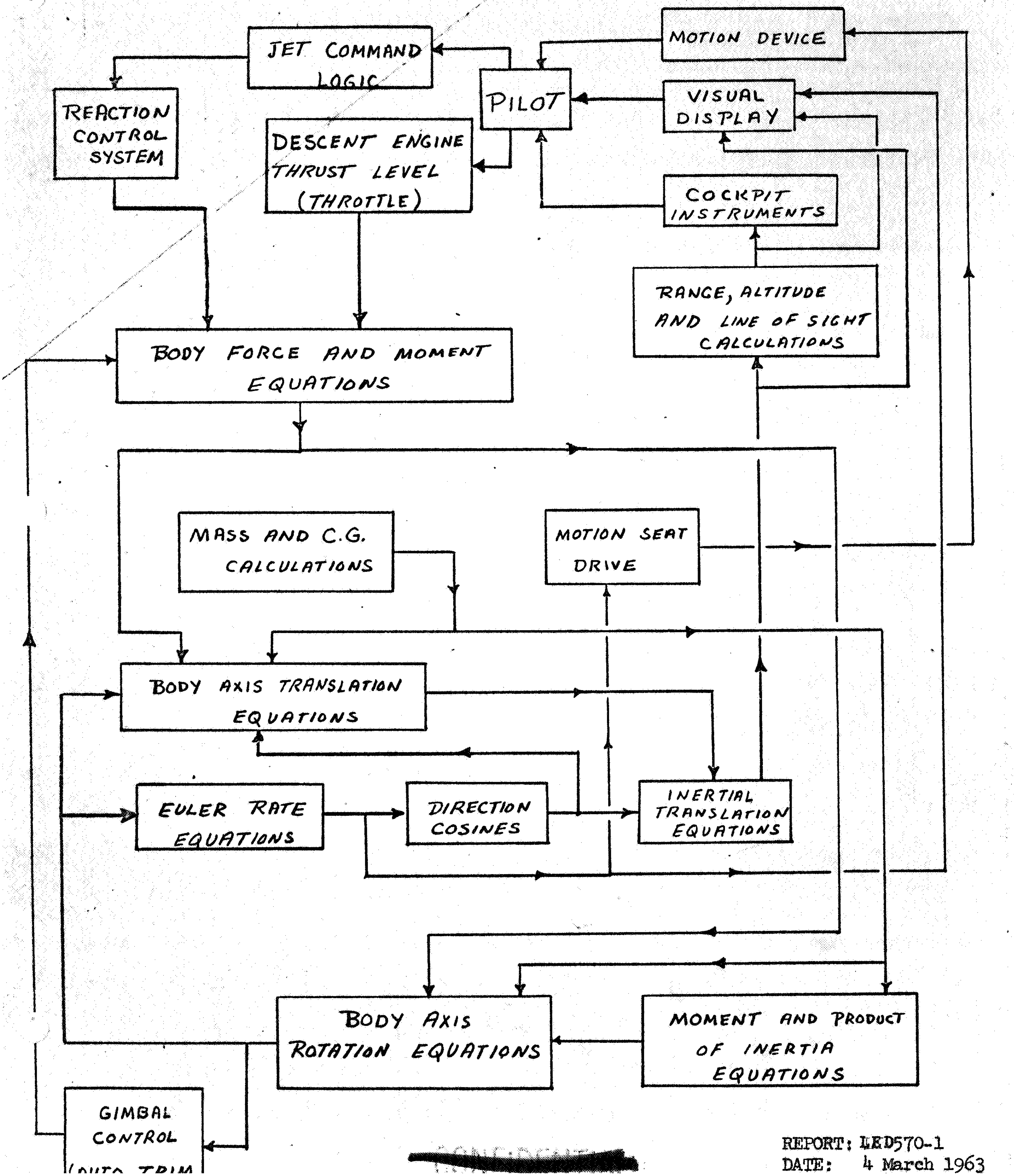
SIMPLIFIED FLOW DIAGRAM

a) Flow Chart for System Equations

b) Interface Flow Diagram

[redacted]

SIMPLIFIED COMPUTER BLOCK DIAGRAM FOR LUNAR HOVER AND LANDING PHASE "A" SIMULATION PROGRAM



REPORT: LED570-1
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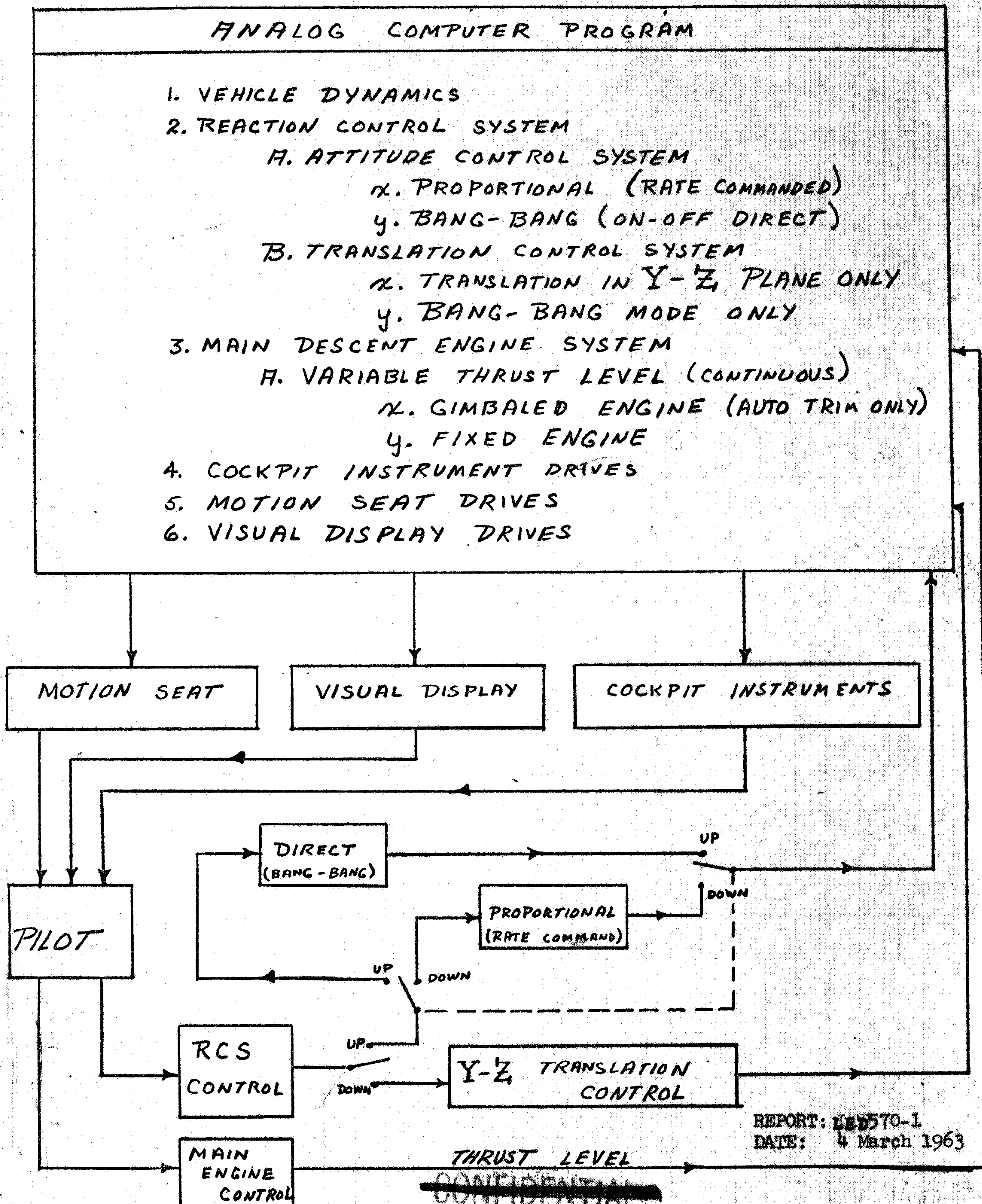
[redacted]

SIMPLIFIED [redacted] DIAGRAM FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION PROGRAM



REPORT: LED570-1
DATE: 4 March 1963

[redacted]

APPENDIX NO. V

SUMMARY OF DEFINED CONSTANT VALUES

SUMMARY OF DEFINED CONSTANT VALUES FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

VALUES SHOWN DEFINED AS OF 20-FEBRUARY-1963

CONSTANT SYMBOL	CONSTANT VALUE	CONSTANT SYMBOL	CONSTANT VALUE
g	+5.3154	x_{Tm}	+6.5
I_{xy}	-78.21	y_{Tm}	0.0
I_{yz}	+94.92	z_{Tm}	0.0
l_D	-2.68	C_m	+9,350
l_{Dp}	+3.91	C_j	+9,660 > 30 MIL SEC +8,380 < 30 MIL SEC
$l_{Dq_r^2}$	+30.4	m_0	+337
$\overline{I_{xy}}$	-78.21	I_{xx_0}	+5,862
I_{xz_0}	+140.0	I_{yy_0}	+6,185
$\overline{I_{yz}}$	+94.92	I_{zz_0}	+6,370
$\frac{dI_{xx}}{dm}$	+17.5	$\bar{x}_{CG_0}$	+9.57
$\frac{dI_{yy}}{dm}$	+21.5	$\bar{y}_{CG_0}$	+0.025
$\frac{dI_{zz}}{dm}$	+20.80	$\bar{z}_{CG_0}$	+0.284
$\frac{dI_{xz}}{dm}$	+1.01	Δm_{mT}	+25.0
$\frac{d\bar{x}_{CG}}{dm}$	-0.0107	Δm_{jT}	+0.547
$\frac{d\bar{y}_{CG}}{dm}$	-0.000325	R_{xg}	+9.13
$\frac{d\bar{z}_{CG}}{dm}$	-0.0013	x_j	+1.66

SUMMARY OF DEFINED CONSTANT VALUES FOR "PHASE "A" LUNAR HOVER AND LANDING SIMULATION CONTINUED

VALUES SHOWN DEFINED AS OF 20-FEBRUARY 1963

CONSTANT SYMBOL	CONSTANT VALUE	CONSTANT SYMBOL	CONSTANT VALUE
l_{j_p}	+5.0		
l_{j_q}	+5.5		
l_{j_r}	+5.5		

APPENDIX NO. VI

SUMMARY OF VARIABLE AND PARAMETER SCALING

SUMMARY OF VARIABLE AND PARAMETER SCALING FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

SYMBOL	RANGE MIN	RANGE MAX	SCALED VALUE
m_2	+0.6	+1.0	$10^2 m_2$
m_3	−0.7	+0.7	$10^2 m_3$
n_1	−0.3	+0.3	$10^2 n_1$
n_2	−0.8	+0.8	$10^2 n_2$
n_3	+0.6	+1.0	$10^2 n_3$
V_X	−50.0	+50.0	V_X
V_Y	−50.0	+50.0	V_Y
V_Z	−50.0	+50.0	V_Z
$\dot{\phi}$	−1.5	+1.5	$50\dot{\phi}$
$\dot{\psi}$	−1.5	+1.5	$50\dot{\psi}$
$\dot{\theta}$	−1.5	+1.5	$50\dot{\theta}$
ϕ	−45.0°	+45.0°	$\phi/20$
ψ	−20.0°	+20.0°	$\psi/2$
θ	−15.0°	+15.0°	$\theta/2$
$\overline{I_{xy}}$	−200.0	+200.0	$10^{-3}\overline{I_{xy}}$
I_{xz_0}	0.0	+500.0	$10^{-3} I_{xz_0}$
$\overline{I_{yz}}$	−200.0	+200.0	$10^{-3}\overline{I_{yz}}$

SYMBOL	RANGE MIN	RANGE MAX	SCALED VALUE
$\frac{dI_{xx}}{dm}$	+10.0	+20.0	$5\times10^{-2}\frac{dI_{xx}}{dm}$
$\frac{dI_{yy}}{dm}$	+10.0	+25.0	$5\times10^{-3}\frac{dI_{yy}}{dm}$
$\frac{dI_{zz}}{dm}$	+10.0	+25.0	$5\times10^{-3}\frac{dI_{zz}}{dm}$
$\frac{dI_{xz}}{dm}$	0.0	+2.0	$5\times10^{-1}\frac{dI_{xz}}{dm}$
$\frac{d\bar{x}_{CG}}{dm}$	−0.04	0.0	$12.5\frac{d\bar{x}_{CG}}{dm}$
$\frac{d\bar{y}_{CG}}{dm}$	−0.0006	+0.0006	$12.5\frac{d\bar{y}_{CG}}{dm}$
$\frac{d\bar{z}_{CG}}{dm}$	−0.002	+0.002	$12.5\frac{d\bar{z}_{CG}}{dm}$
Δm	0.0	+36.0	$5\times10^{-1}\Delta m$
$\dot{m}_m$	0.0	+1.3	NOT SEPARATELY CALCULATED
$\dot{m}_j$	0.0	+0.1	
T_m	0.0	+12,000	$5\times10^{-3} T_m$
T_{jx}	−400.0	+400.0	$10^{-1} T_{jx}$
T_{jy}	−200.0	+200.0	$10^{-1} T_{jy}$
T_{jz}	−200.0	+200.0	$10^{-1} T_{jz}$
$\delta\theta_m$	−10.0°	+10.0°	$800\,\delta\theta_m$ (RAD)
$\delta\psi_m$	−10.0°	+10.0°	$800\,\delta\psi_m$ (RAD)
x_{Tm}	+5.0	+9.0	$25(x_{TM}-\bar{X}_{CG_0})$

[redacted]

SUMMARY OF VARIABLE AND PARAMETER SCALING FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

SYMBOL	RANGE MIN	RANGE MAX	SCALED VALUE
m	298.0	460.0	$m/5$
$\dot{u}$	-50.0	+50.0	$\dot{u}$
u	-70.0	+50.0	u
$\dot{v}$	-30.0	+30.0	$\dot{v}$
v	-50.0	+50.0	v
$\dot{w}$	-30.0	+30.0	$\dot{w}$
w	-50.0	+50.0	w
g	5.3154	5.3154	$g/100$
$\dot{p}$	-0.5	+0.5	$100\dot{p}$
p	-1.0	+1.0	$100p$
$\dot{q}$	-1.0	+1.0	$100\dot{q}$
q	-1.0	+1.0	$100q$
$\dot{r}$	-1.0	+1.0	$100\dot{r}$
r	-1.0	+1.0	$100r$
I_{xx}	5100.0	8600.0	$10^{-2}I_{xx}$
I_{yy}	5400.0	8200.0	$10^{-2}I_{yy}$
I_{zz}	5600.0	8600.0	$10^{-2}I_{zz}$

SYMBOL	RANGE MIN	RANGE MAX	SCALED VALUE
I_{xy}	-200.0	+200.0	$10^{-3}I_{xy}$
I_{xz}	0.0	+500.0	$10^{-1}I_{xz}$
I_{yz}	-200.0	+200.0	$10^{-3}I_{yz}$
$\dot{m}$	-1.5	0.0	$20\dot{m}$
l_D	-2.9	-2.5	$4\times10^{-3}l_D$
l_{Dp}^2	+13.44	+16.0	$5\times10^{-3}l_{Dp}^2$
l_{Dgr}^2	+20.0	+40.0	$5\times10^{-3}l_{Dgr}^2$
B_x	-400.0	+12,400.0	$5\times10^{-3}B_x$
B_y	-2000.0	+2000.0	$5\times10^{-2}B_y$
B_z	-2000.0	+2000.0	$5\times10^{-2}B_z$
L	-1500.0	+1500.0	$5\times10^{-2}L$
M	-3000.0	+3000.0	$2\times10^{-2}M$
N	-3000.0	+3000.0	$2\times10^{-2}N$
l_1	+0.9	+1.0	$10^2 l_1$
l_2	-0.5	+0.5	$10^2 l_2$
l_3	-0.5	+0.5	$10^2 l_3$
m_1	-0.4	+0.4	$10^2 m_1$

[redacted]

SUMMARY OF VARIABLE AND PARAMETER SCALING FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

SYMBOL	RANGE MIN	RANGE MAX	SCALED VALUE
y_{Tm}	0.0	0.0	$25(y_{TM}-\bar{y}_{CG_0})$
z_{Tm}	0.0	0.0	$25(z_{TM}-\bar{z}_{CG_0})$
x_m	-6.0	0.0	$25x_m$
y_m	-0.3	+0.3	$25y_m$
z_m	-0.4	+0.4	$25z_m$
$\bar{x}_{CG}$	+8.0	+11.0	NOT
$\bar{y}_{CG}$	-0.3	+0.3	CALCULATED
$\bar{z}_{CG}$	-0.4	+0.4	SEPARATELY
I_m	0.0	+350,000.0	$2\times10^{-4}I_m$
I_j	0.0	+10,000.0	$10^{-2}I_j$
C_m	+6,000.0	+10,000.0	$\frac{4000}{C_m}$
C_j	+6,000.0	+10,000.0	$\frac{200}{C_j}$
ΣT_j	0.0	+800.0	
Δm_m	0.0	+35.0	NOT CALC.
Δm_j	0.0	+1.0	SEPARATELY
R_X	0.0	+2000.0	$5\times10^{-2}R_X$
R_Y	-1,000.0	+1,000.0	$5\times10^{-2}R_Y$

SYMBOL	RANGE MIN	RANGE MAX	SCALED VALUE
R_Z	-1,000.0	+1,000.0	$5\times10^{-2}R_Z$
R_S	0.0	+1,500.0	$5\times10^{-2}R_S$
$R=\rho$	0.0	+3,000.0	$5\times10^{-2}R_S$
A	-90.0°	+180.0°	$\frac{A}{2}(°)$
E	0.0	+90.0°	$\frac{E}{2}(°)$
R_N	-1,500.0	+1,500.0	$5\times10^{-2}R_N$
$\dot{R}_N$	-100.0	+100.0	$\mathring{R}_N$
$\dot{R}_S$	-100.0	+100.0	$\mathring{R}_S$
ε_ϕ	-135.0°	+225.0°	$5\times10^{-1}\varepsilon_\phi$
m_0	+298.0	+460.0	$2\times10^{-1}m_0$
I_{xx_0}	+5,100	+8,600.0	$10^{-2}I_{xx_0}$
I_{yy_0}	+5,400.0	+8,200.0	$10^{-2}I_{yy_0}$
I_{zz_0}	+5,600.0	+8,600.0	$10^{-2}I_{zz_0}$
$\bar{x}_{CG_0}$	+8.0	+11.0	NOT
$\bar{y}_{CG_0}$	-0.3	+0.3	SET SEPARATELY
$\bar{z}_{CG_0}$	-0.4	+0.4	
θ_0	-15.0°	+15.0°	$\frac{\theta}{2}(°)$

[redacted]

SUMMARY OF VARIABLE AND PARAMETER SCALING FOR PHASE "A" LUNAR HOVER AND LANDING SIMULATION

SYMBOL	RANGE MIN	RANGE MAX	SCALED VALUE
ψ_0	−20.0°	+20.0°	$\frac{\psi}{2}(°)$
ϕ_0	−45.0°	+45.0°	$\frac{\phi}{20}(°)$
R_{x_0}	0.0	+2,000.0	$5\times10^{-2} R_{x_0}$
R_{Y_0}	−1,000.0	+1,000.0	$5\times10^{-2} R_{y_0}$
R_{z_0}	−1,000.0	+1,000.0	$5\times10^{-2} R_{z_0}$
u_0	−70.0	+50.0	u_0
v_0	−50.0	+50.0	v_0
w_0	−50.0	+50.0	w_0
p_0	−1.0	+1.0	$100 p_0$
q_0	−1.0	+1.0	$100 q_0$
r_0	−1.0	+1.0	$100 r_0$
Δm_{mT}	+20.0	+35.0	
Δm_{jT}	+0.3	+1.0	
L_j	−1,200.0	+1,200.0	
M_j	−1,700.0	+1,700.0	NOT CALC
N_j	−1,700.0	+1,700.0	SEPARATED
R_{xg}	+7.0	+11.0	$5\times10^{-2} R_{xG}$

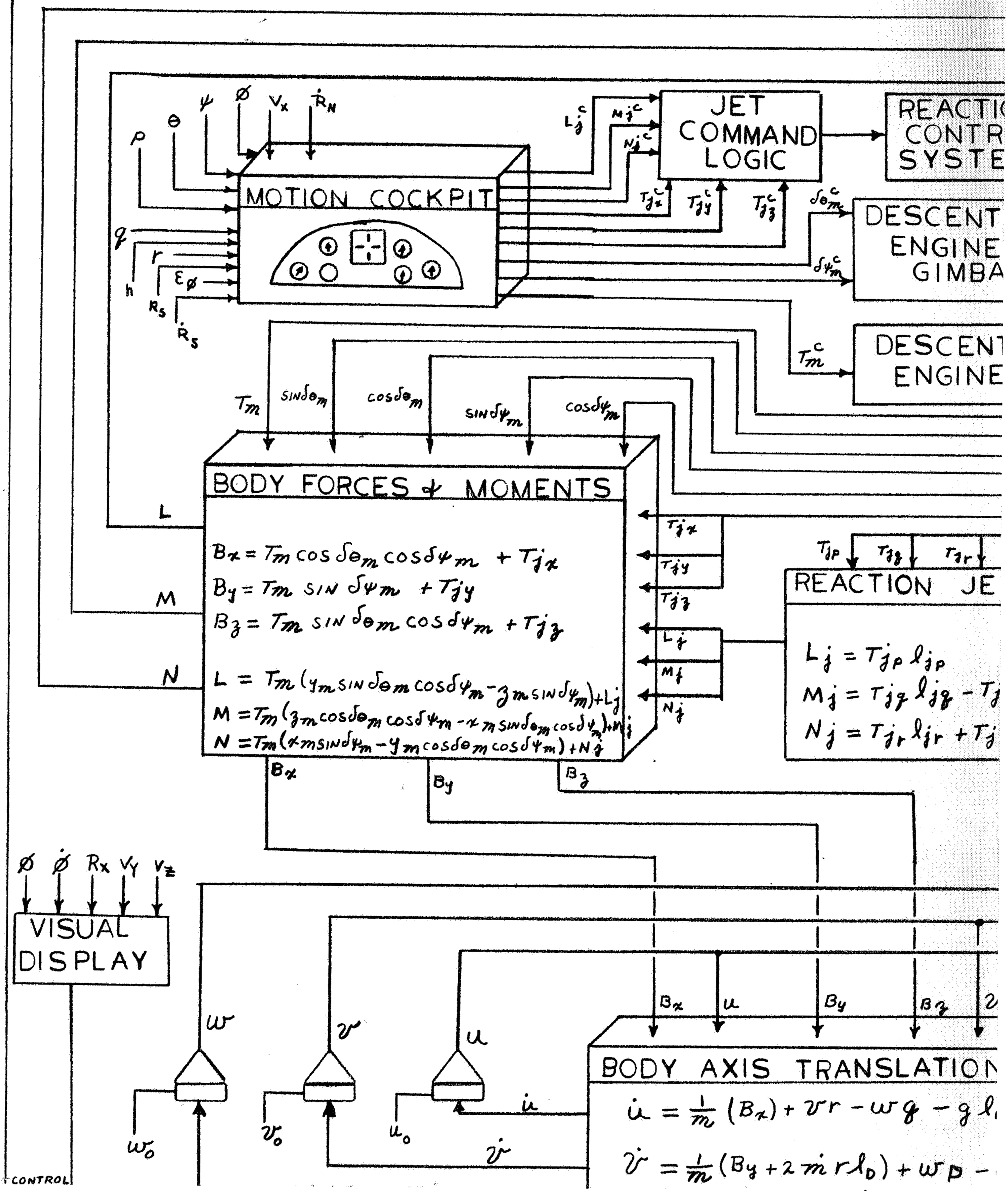
SYMBOL	RANGE MIN	RANGE MAX	SCALED VALUE
h	0.0	+2,000.0	$5\times10^{-2} h$
T_{jp}	−200.0	+200.0	$2.5\times10^{-1} T_{jp}$
T_{jq}	−200.0	+200.0	$2.5\times10^{-1} T_{jq}$
T_{jr}	−200.0	+200.0	$2.5\times10^{-1} T_{jr}$
α_j	+1.5	+2.0	
l_{jp}	+4.0	+6.0	$4\times10^{-2} l_{jp}$
l_{jq}	+4.0	+6.0	$4\times10^{-2} l_{jq}$
l_{jr}	+4.0	+6.0	$4\times10^{-2} l_{jr}$
I_{jx}	0.0	+2,000.0	
I_{jy}	0.0	+5,000.0	
I_{jz}	0.0	+5,000.0	
I_{jp}	0.0	+5,000.0	$10^{-2} I_{jp}$
I_{jq}	0.0	+5,000.0	$10^{-2} I_{jq}$
I_{jr}	0.0	+5,000.0	$10^{-2} I_{jr}$
l_4			
l_5			

APPENDIX NO. VII

DETAILED ANALOG COMPUTER FLOW CHART

ANALOG COMPUTER FLOW CHART FO

BY: R. BEADLE, JR.
DATE: 10-FEBRUARY-1963 #1



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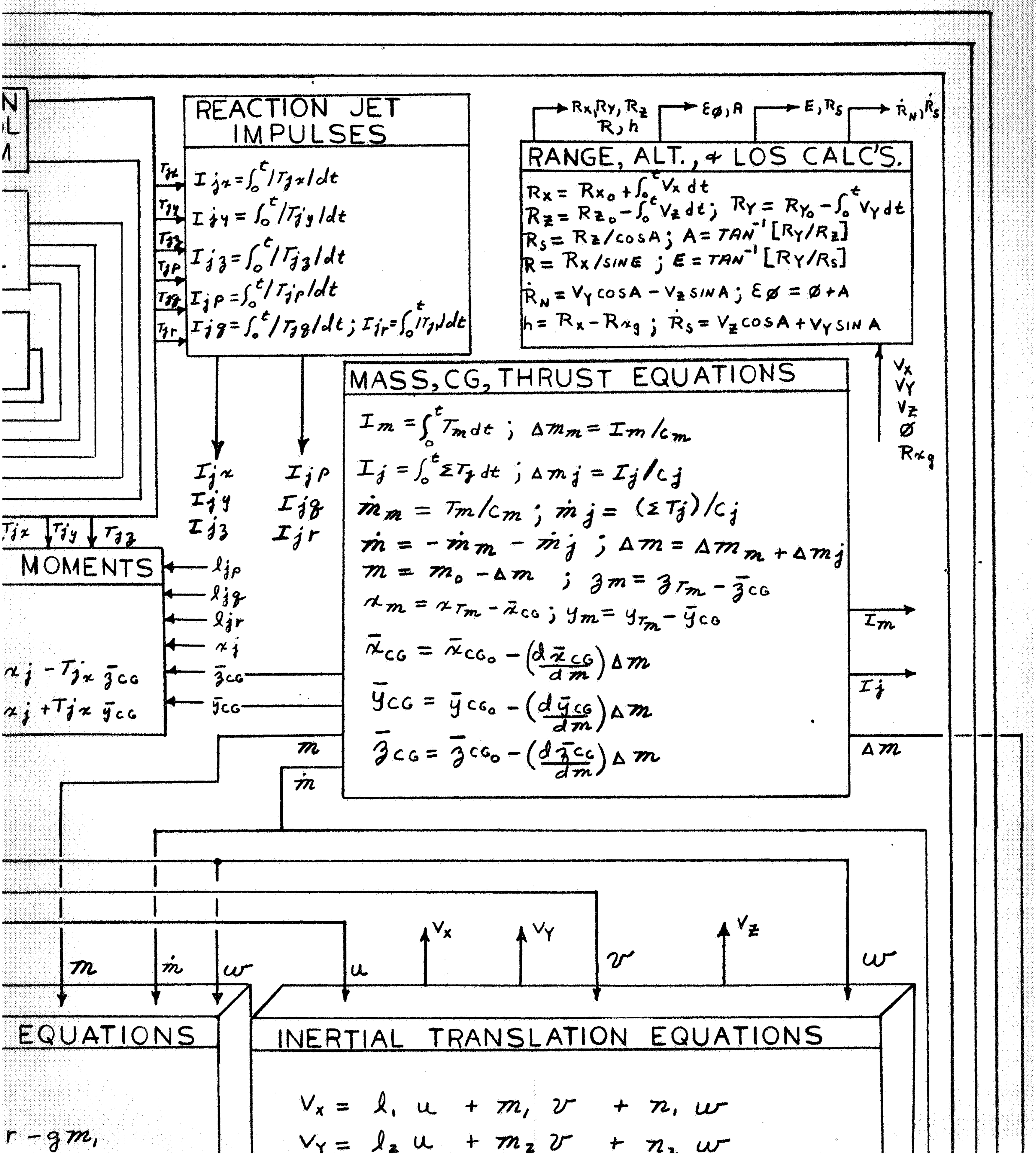
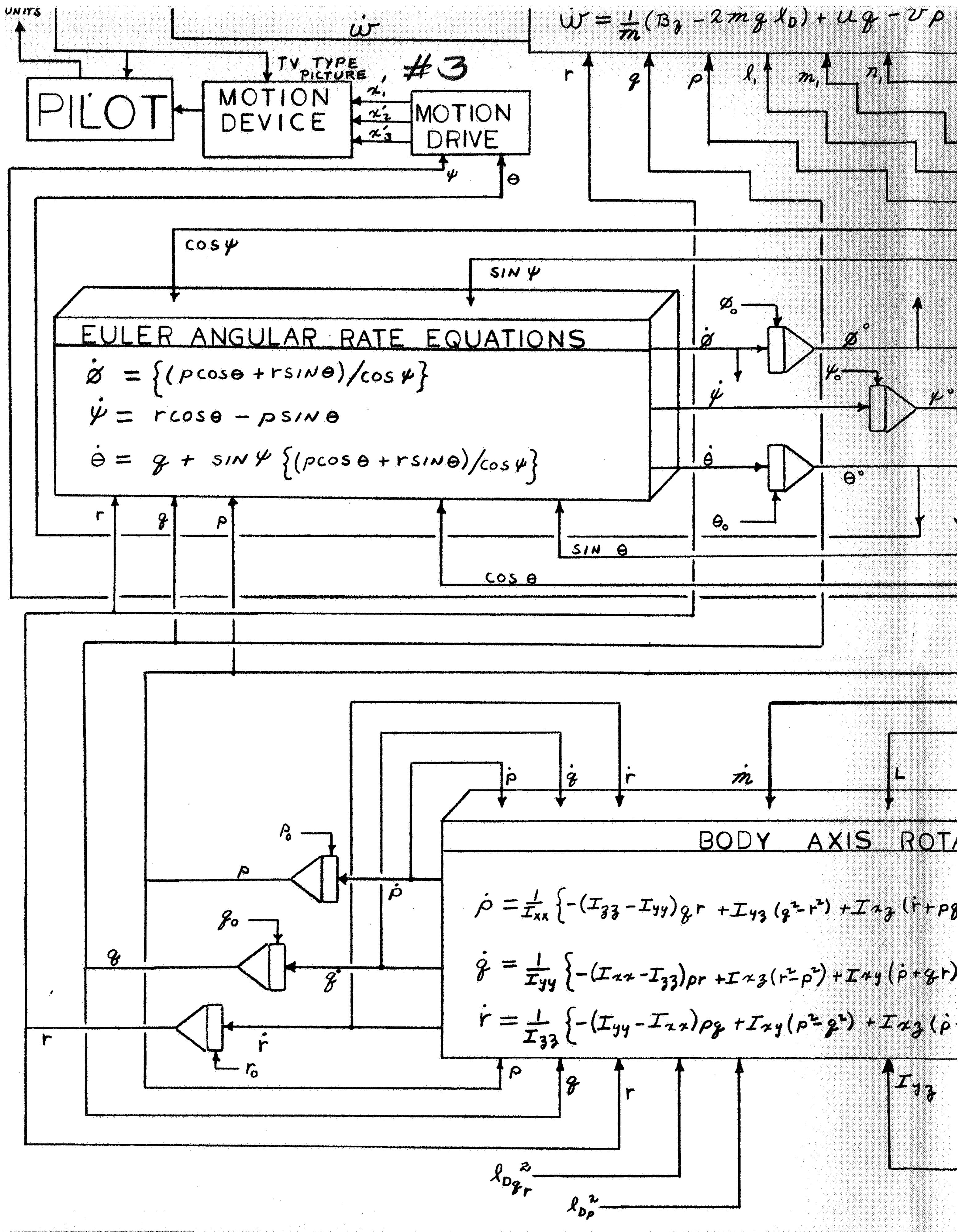
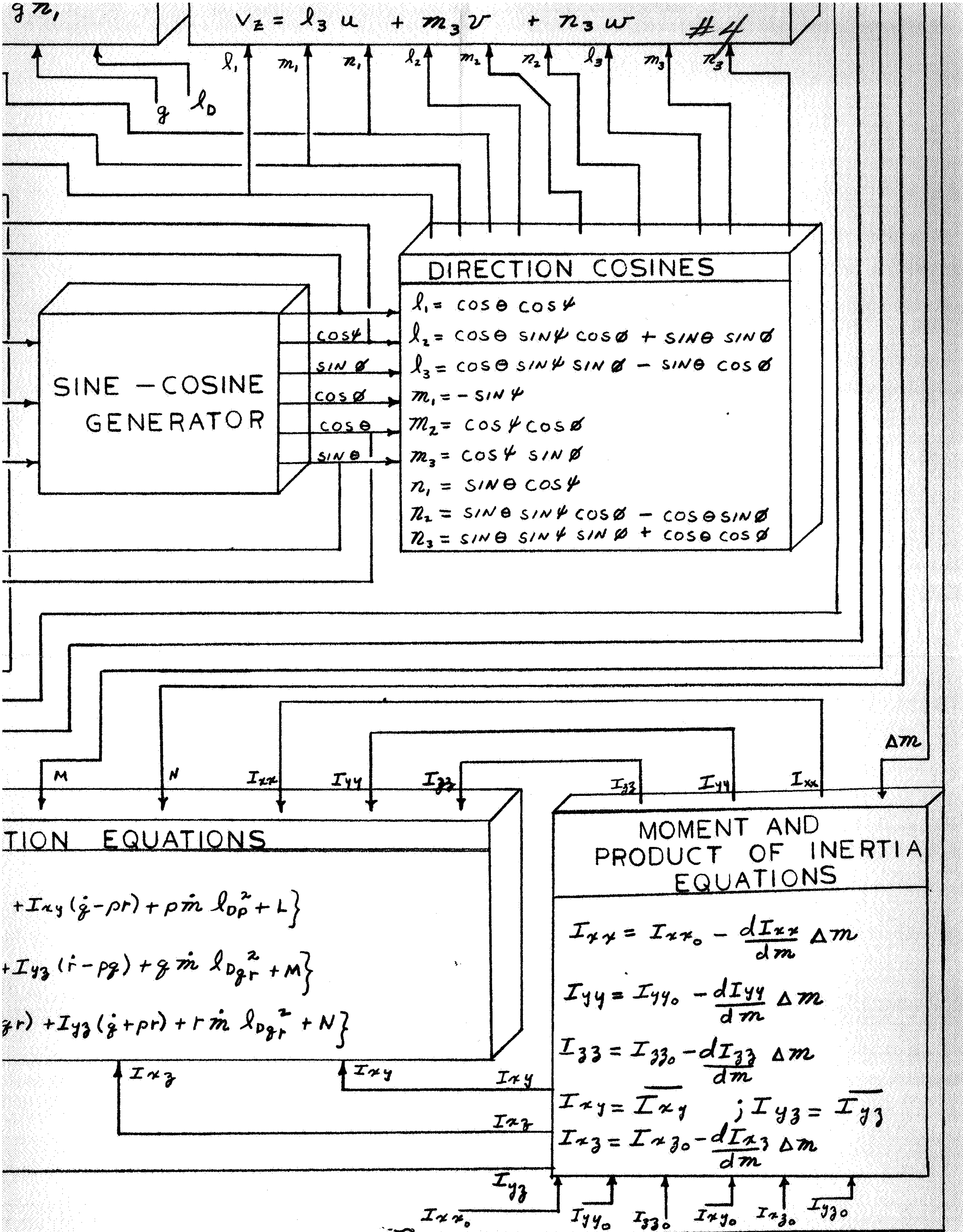
R LUNAR HOVER AND LANDING #2
PHASE "A" SIMULATION PROGRAM





UNITS
TV TYPE PICTURE
#3
PILOT
MOTION DEVICE
MOTION DRIVE
$\dot{w} = \frac{1}{m}(B_z - 2mg\,l_D) + ug - vp$
x_1' x_2' x_3'
ψ θ
r q p l_1 m_1 n_1
COS ψ
SIN ψ
EULER ANGULAR RATE EQUATIONS
$\dot{\phi} = \{(p\cos\theta + r\sin\theta)/\cos\psi\}$
$\dot{\psi} = r\cos\theta - p\sin\theta$
$\dot{\theta} = q + \sin\psi\,\{(p\cos\theta + r\sin\theta)/\cos\psi\}$
ϕ_0 ϕ° ψ_0 ψ° θ° θ_0
SIN θ
COS θ
$\dot{p}$ $\dot{q}$ $\dot{r}$ $\dot{m}$ L
BODY AXIS ROT
$\dot{p} = \frac{1}{I_{xx}}\{-(I_{zz}-I_{yy})qr + I_{yz}(q^2-r^2) + I_{xz}(\dot{r}+pq$
$\dot{q} = \frac{1}{I_{yy}}\{-(I_{xx}-I_{zz})pr + I_{xz}(r^2-p^2) + I_{xy}(\dot{p}+qr)$
$\dot{r} = \frac{1}{I_{zz}}\{-(I_{yy}-I_{xx})pq + I_{xy}(p^2-q^2) + I_{xz}(\dot{p}$
p_0 q_0 r_0
I_{yz}
$l_{Dq_r}^2$
l_{Dp}^2



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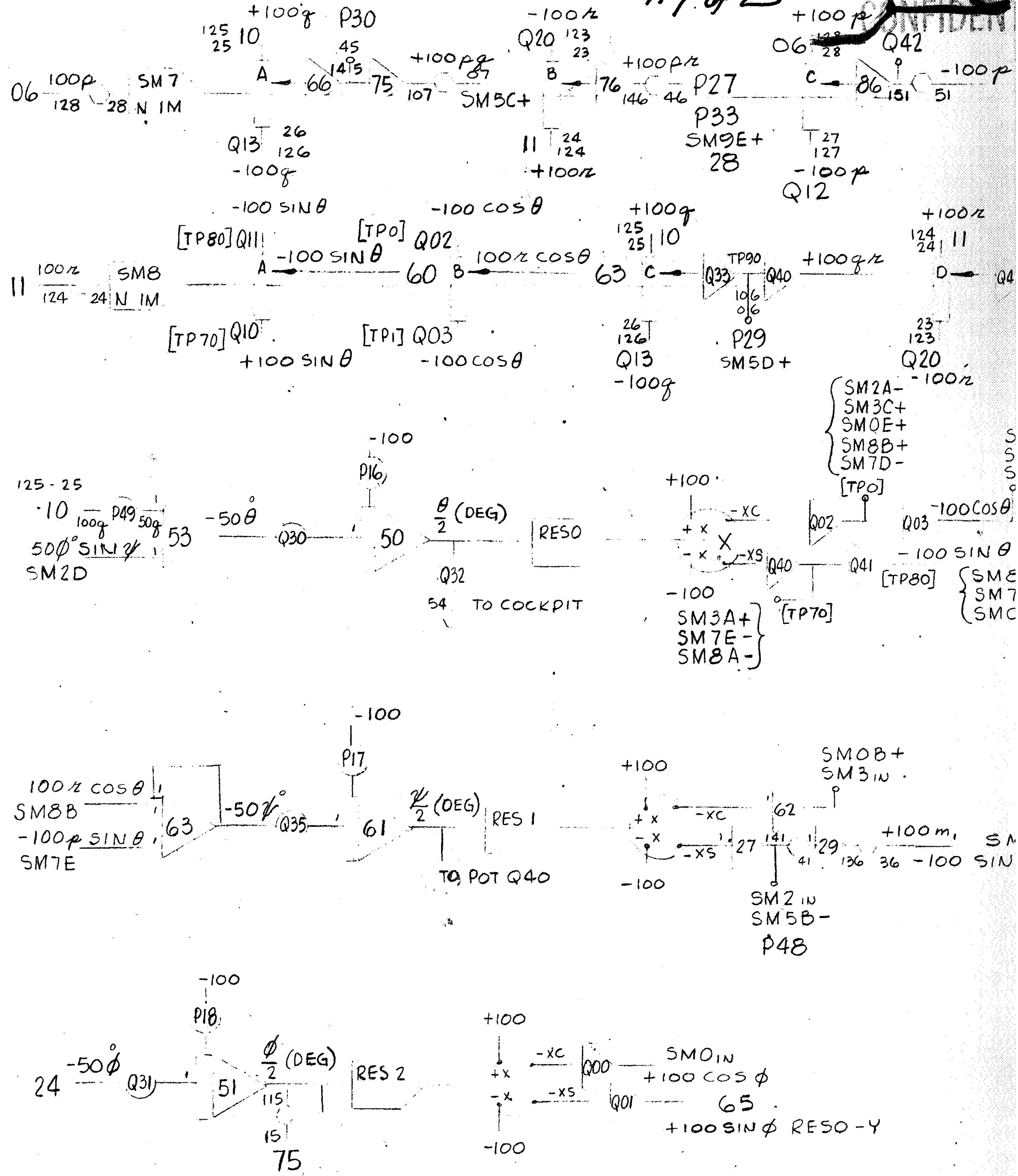
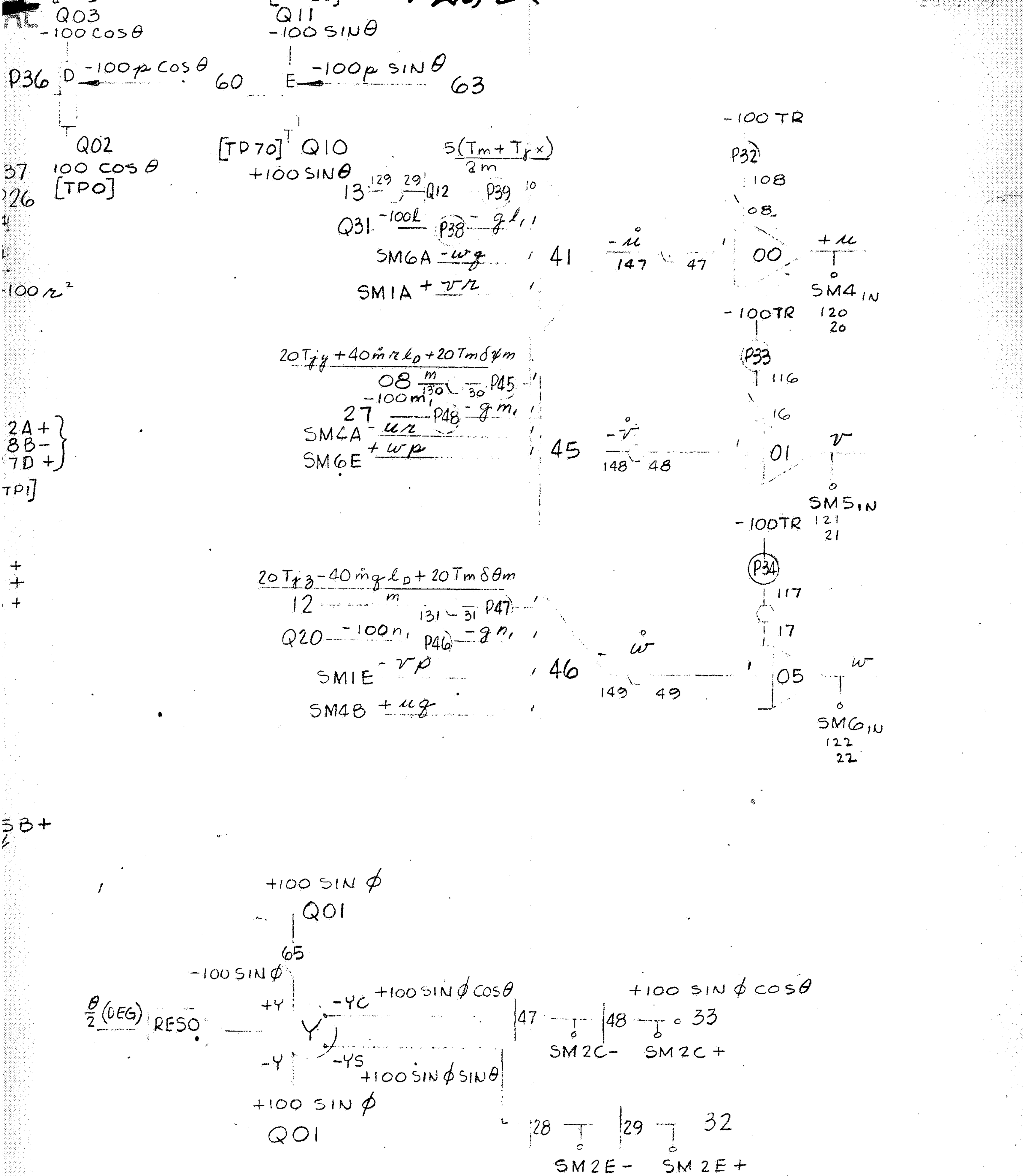
APPENDIX NO. VIII

ANALOG COMPUTER PROGRAM

#1 of 2 [redacted]

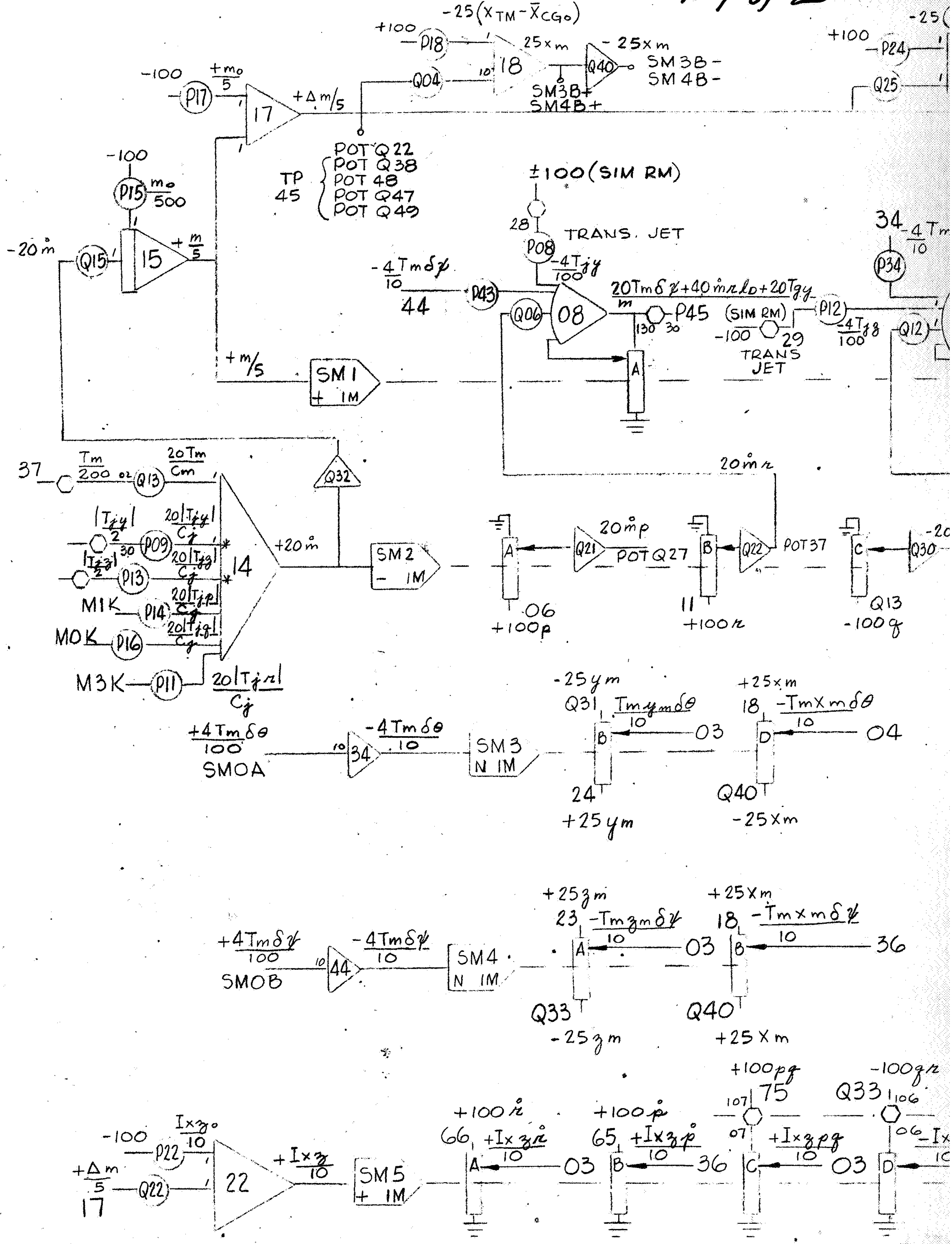




EULER ANGLES AND BODY AXIS TRANSLATIONS

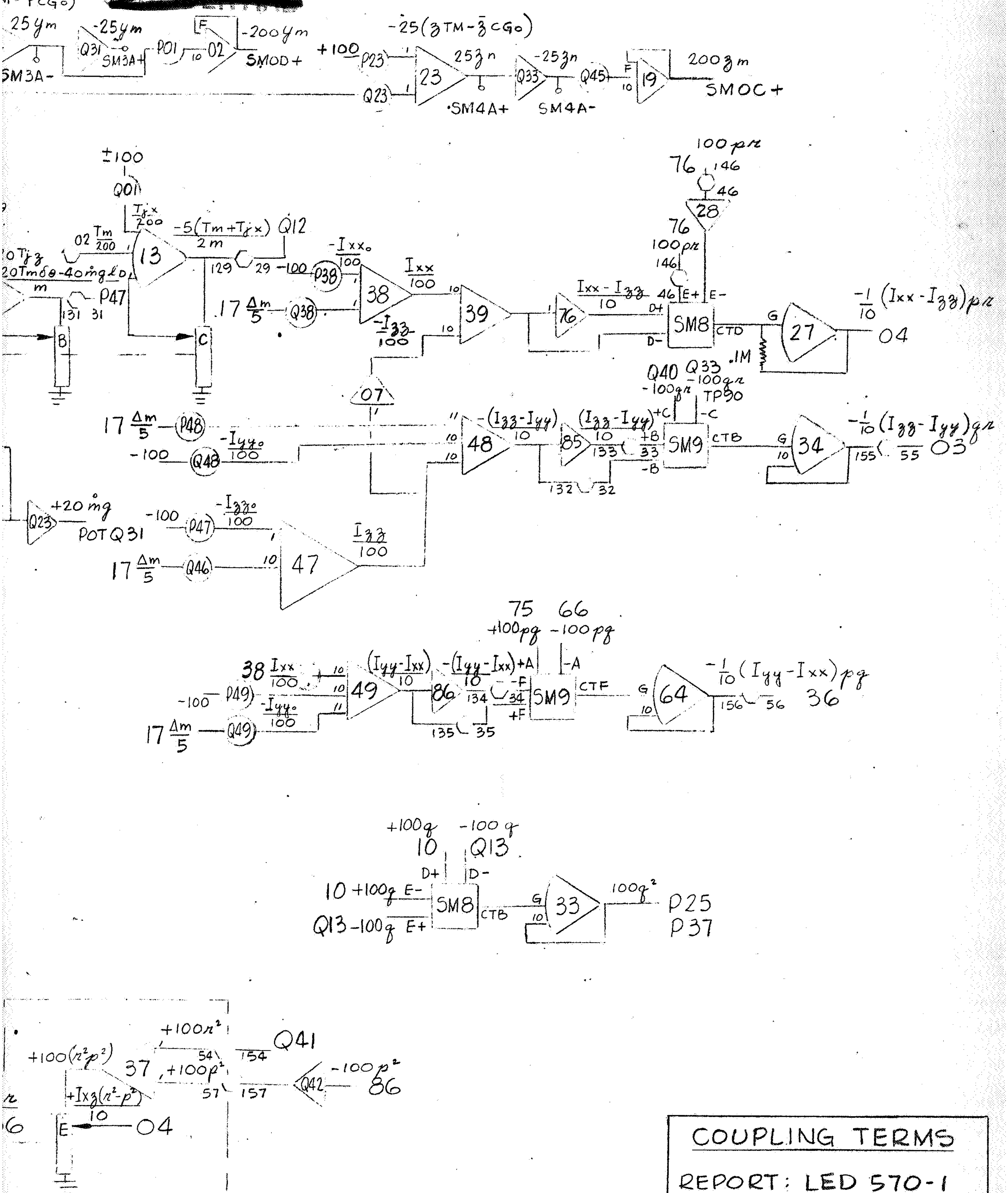
REPORT: LED 570-1

DATE: 4 MARCH 1963


-25(X_TM - X̄_CGo)
+100
P18
25xm
18
-25xm
Q40
SM3B-
SM4B-
SM3B+
SM4B+
Q04
-100
P17
+mo/5
17
+Δm/5
POT Q22
POT Q38
POT 48
POT Q47
POT Q49
TP 45
-100
P15
mo/500
-20ṁ
Q15
15
+m/5
±100(SIM RM)
28
P08
TRANS. JET
-4Tjy/100
-4Tmδψ/10
44
P43
Q06
08
20Tmδψ+40ṁrlo+20Tgy/m
P45
(SIM RM)
-100
29
TRANS JET
P12
-4Tjz/100
Q12
+100
P24
Q25
34
-4Tm/10
P34
+m/5
SM1
+ IM
A
20ṁr
37
Tm/200
Q13
20Tm/Cm
Q32
+20ṁ
14
SM2
- IM
P09
P13
M1K
P14
M0K
P16
M3K
P11
20|Tjx|/Cj
20ṁp
Q21
POT Q27
Q22
POT 37
Q30
06
+100p
11
+100r
Q13
-100q
-25ym
Q31
Tmymδθ/10
+25xm
18
-TmXmδθ/10
+4Tmδθ/100
SMOA
34
-4Tmδθ/10
SM3
N IM
B
03
D
04
24
+25ym
Q40
-25Xm
+25zm
23
-Tmzmδψ/10
+25Xm
18
-Tmxmδψ/10
+4Tmδψ/100
SMOB
44
-4Tmδψ/10
SM4
N IM
03
36
Q33
-25zm
Q40
+25Xm
+100pq
75
-100qr
Q33
-100
P22
Ixzo/10
+Δm/5
Q22
17
22
+Ixz/10
SM5
+ IM
+100ṙ
66
+Ixzṙ/10
+100ṗ
65
+Ixzṗ/10
+Ixzpq/10
03
36
03

[redacted]

#2 of 2



COUPLING TERMS

REPORT: LED 570-1

DATE: 4 MARCH 1963

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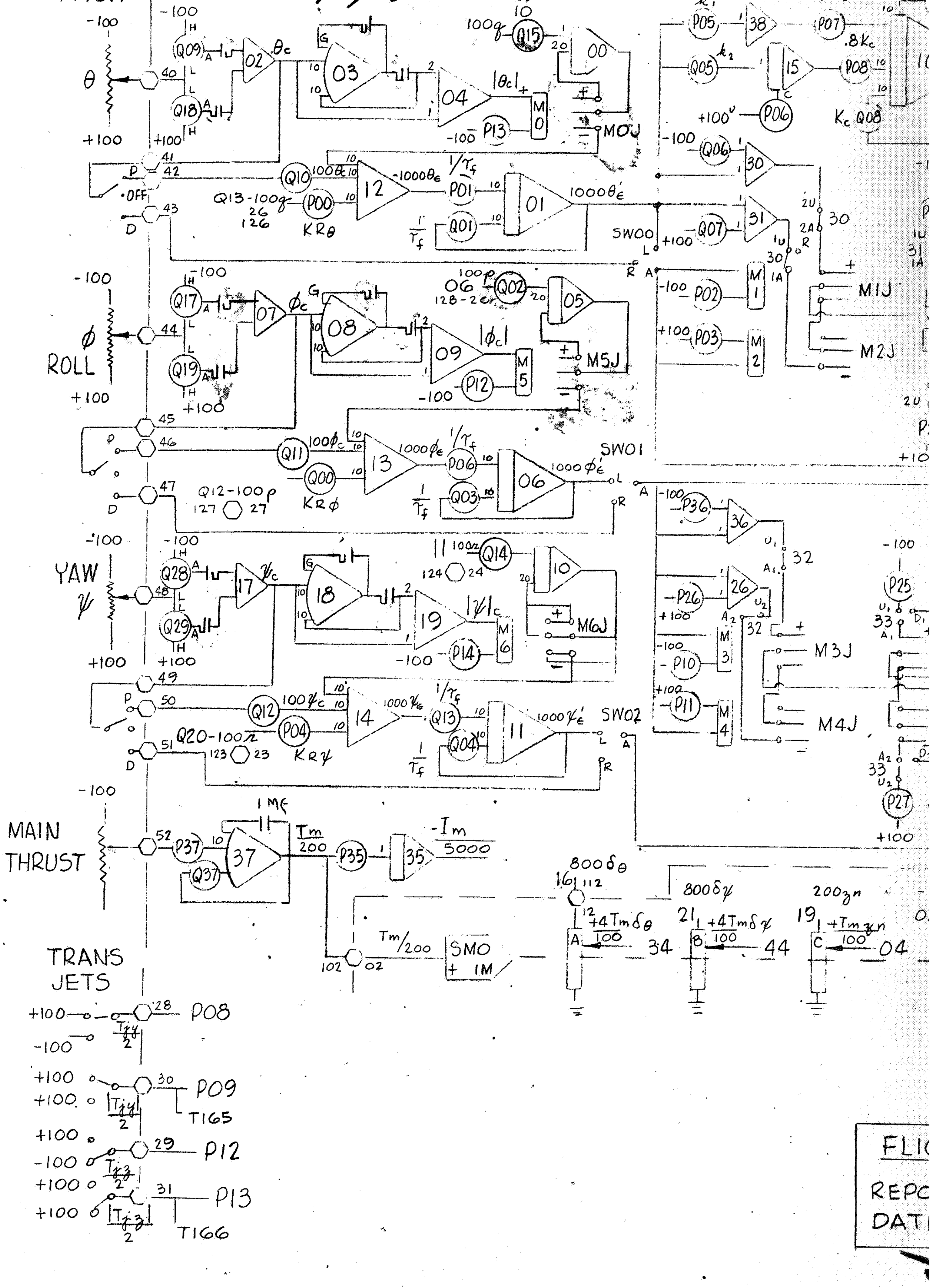
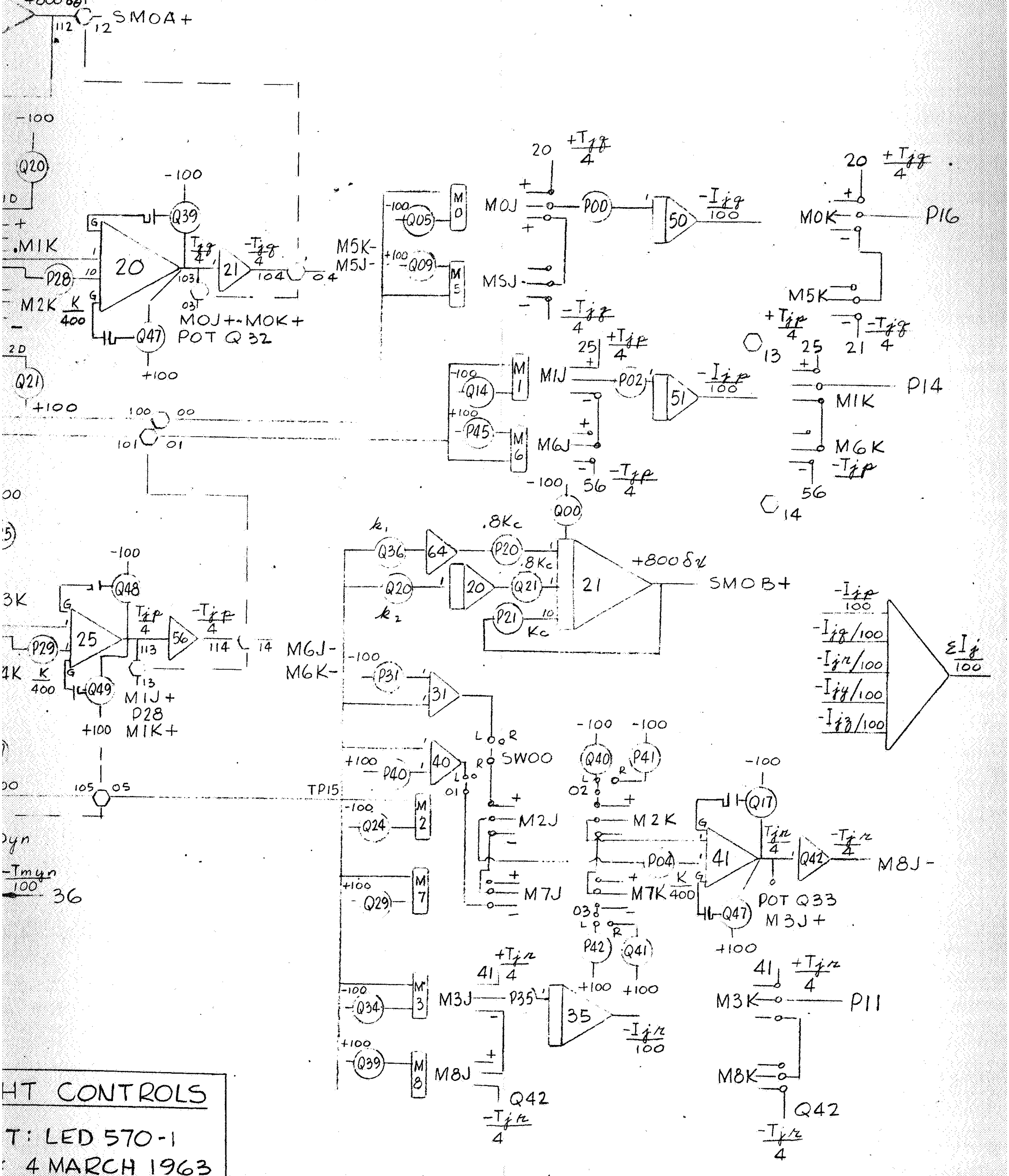
#1 of 2



PITCH
θ
ROLL
φ
YAW
ψ
MAIN THRUST
TRANS JETS
M0J
M1J
M2J
M3J
M4J
M5J
M6J
SW00
SW01
SW02
KRθ
KRφ
KRψ
Q13-100q
Q12-100p
Q20-100r
1 MF
Tm/200
-Im/5000
800δθ
800δψ
200zn
+4Tmδθ/100
+4Tmδψ/100
+Tmzn/100
SMO + IM
P08
P09
P12
P13
T165
T166
FLI
REPO
DAT

[redacted]



HT CONTROLS

T: LED 570-1

4 MARCH 1963

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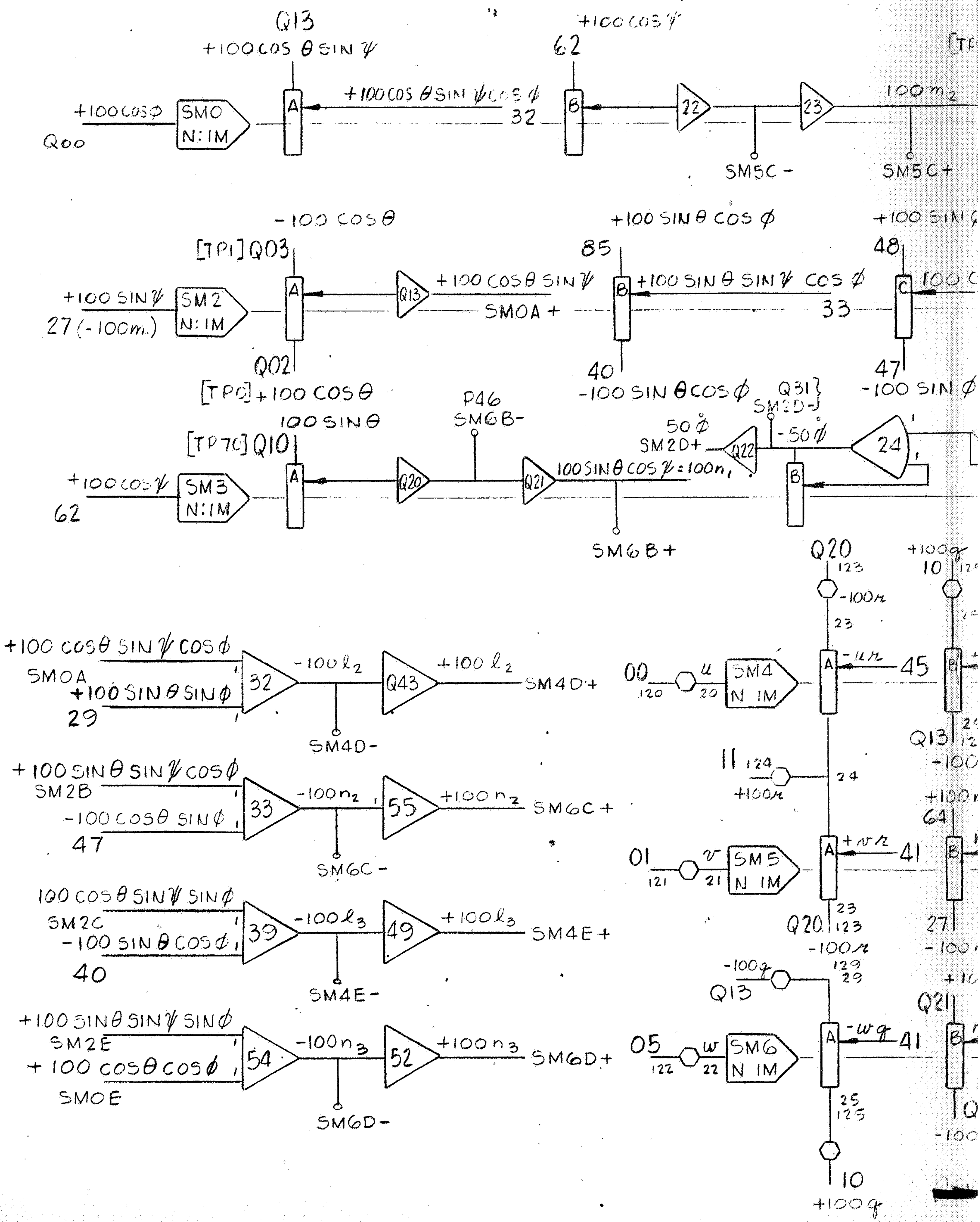
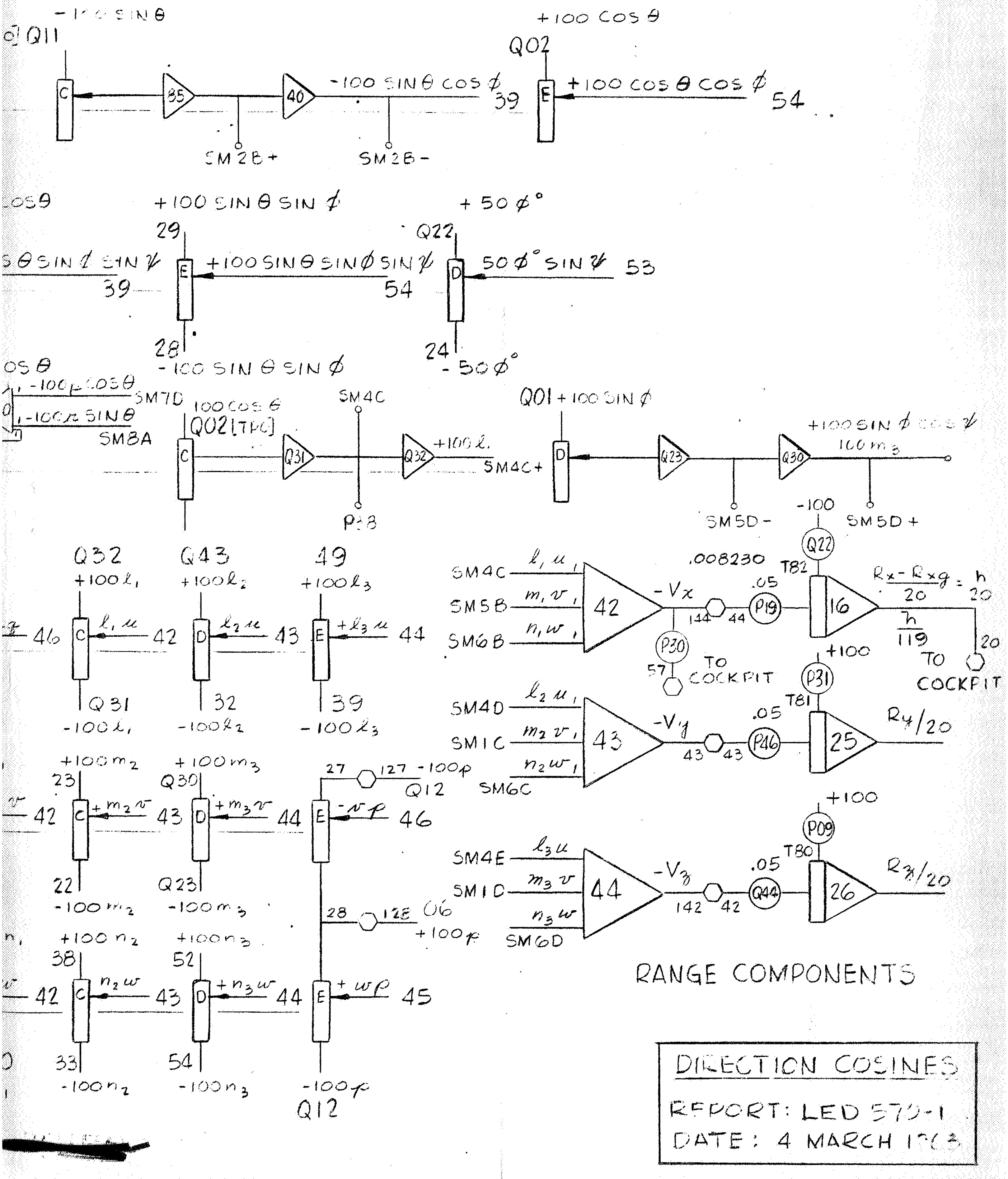
Report: LED 570-1
Date: 4 March 1963

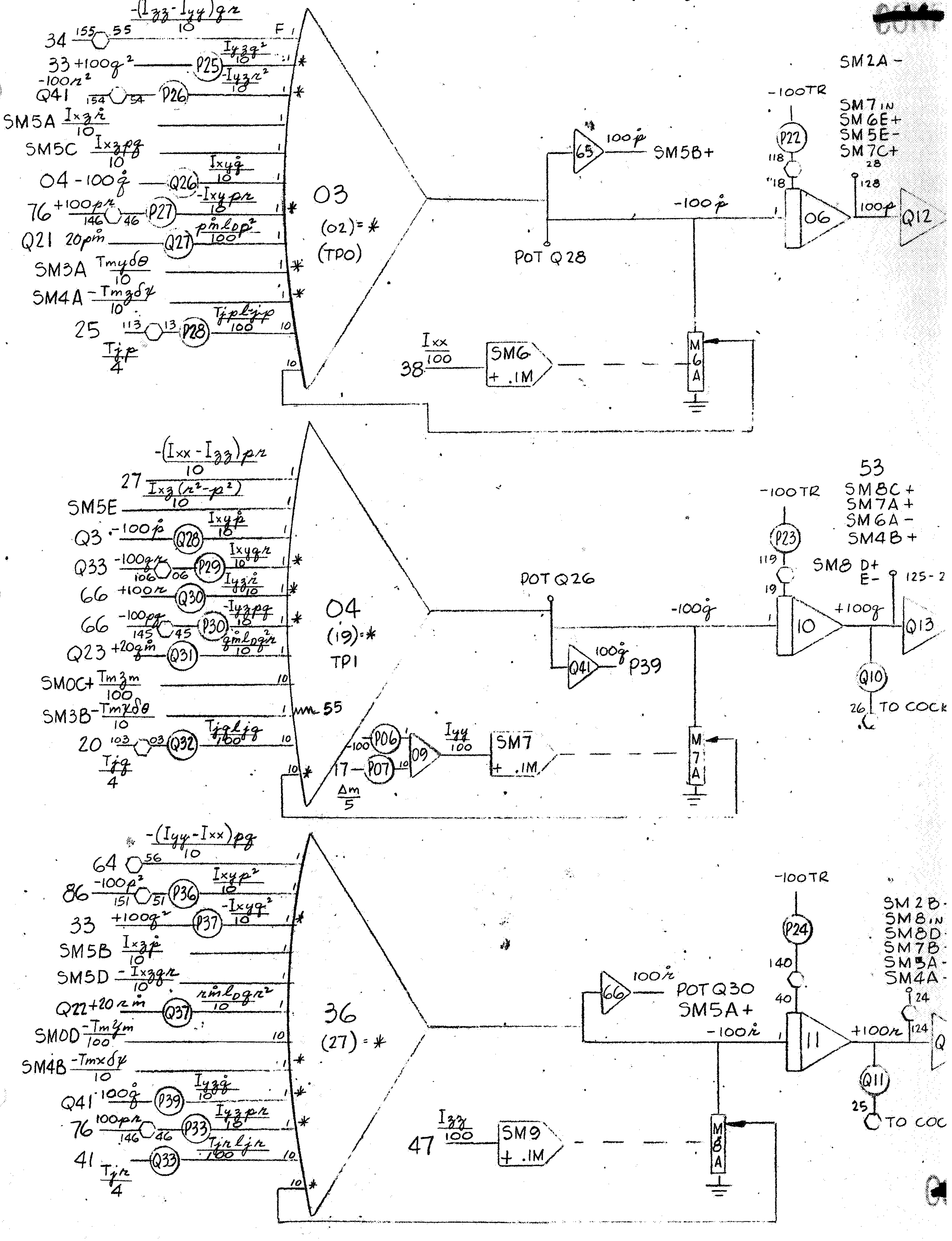

Q13
+100 COS θ SIN ψ
+100 COS ψ
62
+100 COS ϕ
Q00
SM0
N:IM
A
+100 COS θ SIN ψ COS ϕ
32
B
22
23
100 m_2
SM5C −
SM5C +
−100 COS θ
+100 SIN θ COS ϕ
+100 SIN
[TP1] Q03
85
48
+100 SIN ψ
27 (−100m.)
SM2
N:IM
Q13
+100 COS θ SIN ψ
SM0A +
+100 SIN θ SIN ψ COS ϕ
33
C
Q02
40
47
[TP0] +100 COS θ
−100 SIN θ COS ϕ
−100 SIN ϕ
100 SIN θ
P46
SM6B −
Q31
SM2D −
50 ϕ
SM2D +
Q22
−50 ϕ
24
[TP70] Q10
+100 COS ψ
62
SM3
N:IM
Q20
Q21
100 SIN θ COS ψ = 100 n_1
SM6B +
Q20
+100 q
10
−100 r
23
+100 COS θ SIN ψ COS ϕ
SM0A
+100 SIN θ SIN ϕ
29
32
−100 l_2
Q43
+100 l_2
SM4D +
SM4D −
00
120
u
20
SM4
N IM
−ur
45
Q13
11
124
+100 r
24
+100 SIN θ SIN ψ COS ϕ
SM2B
−100 COS θ SIN ϕ
47
33
−100 n_2
55
+100 n_2
SM6C +
SM6C −
64
01
121
v
21
SM5
N IM
+vr
41
100 COS θ SIN ψ SIN ϕ
SM2C
−100 SIN θ COS ϕ
40
39
−100 l_3
49
+100 l_3
SM4E +
SM4E −
Q20
123
−100 r
27
−100 q
Q13
129
29
Q21
+100 SIN θ SIN ψ SIN ϕ
SM2E
+100 COS θ COS ϕ
SME
54
−100 n_3
52
+100 n_3
SM6D +
SM6D −
05
122
w
22
SM6
N IM
−wq
41
25
125
10
+100 q

#2 Q2



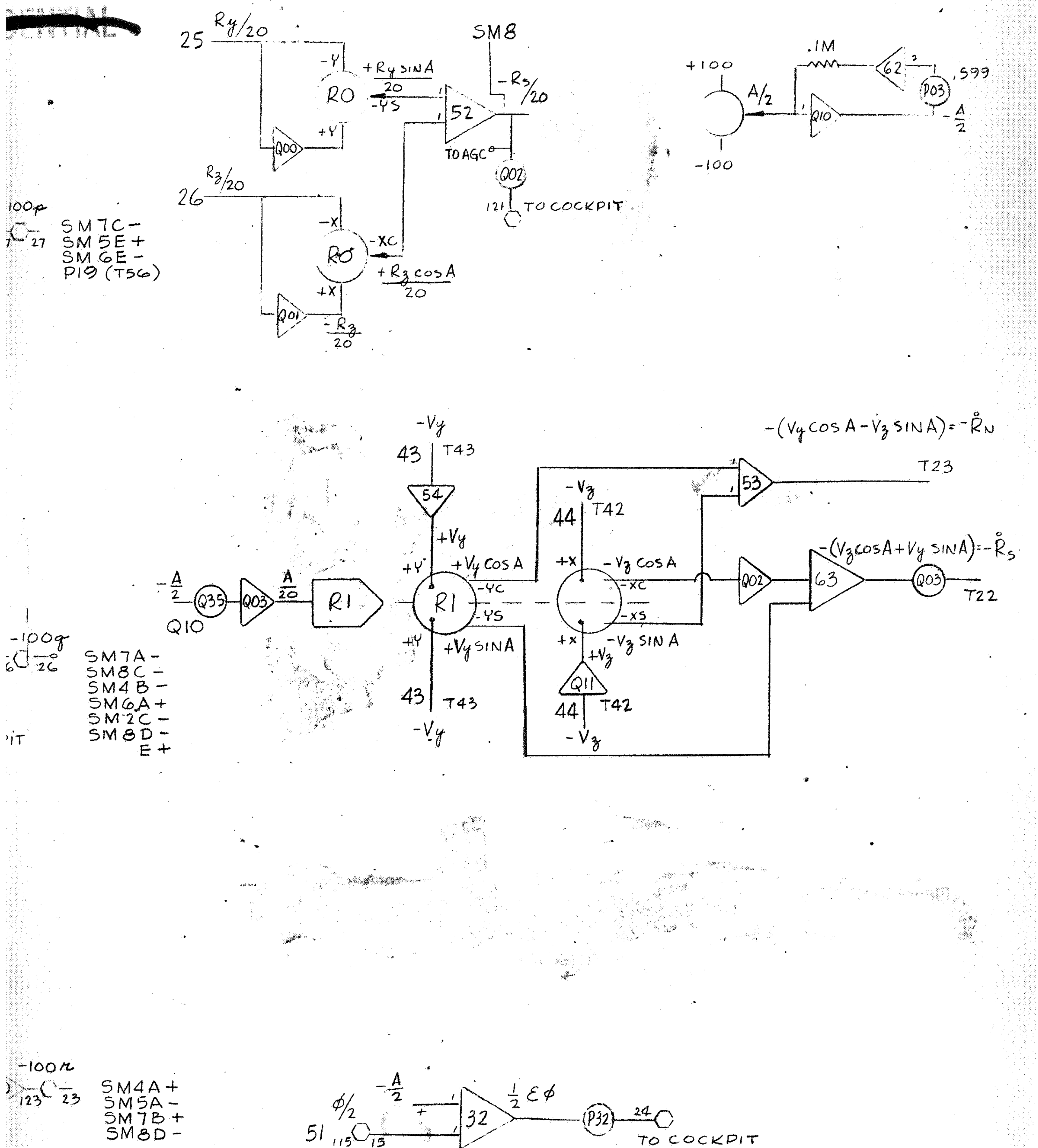
-100 SIN θ
Q11
35
40
-100 SIN θ COS φ
39
+100 COS θ
Q02
+100 COS θ COS φ
54
SM2B+
SM2B-
+100 SIN θ SIN φ
29
+100 SIN θ SIN φ SIN ψ
54
28
-100 SIN θ SIN φ
+50 φ°
Q22
50 φ° SIN ψ
53
24
-50 φ°
SM7D
SM8A
100 COS θ
Q02 [TPC]
Q31
Q32
+100 l
SM4C
SM4C+
Q01 +100 SIN φ
Q23
Q30
+100 SIN φ COS ψ
100 m3
SM5D-
SM5D+
-100
Q22
Q32
+100 l1
46
l, u
42
Q31
-100 l1
Q43
+100 l2
43
32
-100 l2
49
+100 l3
44
39
-100 l3
SM4C
SM5B
SM6B
l1 u1
m1 v1
n1 w1
42
-Vx
.008230
T82
.05
P19
16
P30
57
TO COCKPIT
h/119
TO COCKPIT
20
+100
P31
T81
SM4D
SM1C
SM6C
l2 u1
m2 v1
n2 w1
43
-Vy
P46
25
Ry/20
+100
P09
T80
SM4E
SM1D
SM6D
l3 u
m3 v
n3 w
44
-Vz
Q44
26
Rz/20
+100 m2
23
+m2 v
22
-100 m2
+100 m3
Q30
+m3 v
Q23
-100 m3
27
127
-100 ρ
Q12
-vρ
46
28
128
06
+100 ρ
+100 n2
38
n2 w
33
-100 n2
+100 n3
52
+n3 w
54
-100 n3
+wρ
45
-100 ρ
Q12
RANGE COMPONENTS
DIRECTION COSINES
REPORT: LED 570-1
DATE: 4 MARCH 1963

#1 of 2



03
(02) = *
(TP0)
POT Q28
100p SM5B+
-100p
06
Q12
-100TR
P22
SM2A -
SM7 IN
SM6E+
SM5E-
SM7C+
SM5A
SM5C
SM3A
SM4A
Q41
Q21
SM6 + .1M
M6A
04
(19) = *
TP1
POT Q26
-100q
+100q
10
Q13
Q10
TO COCK
-100TR
P23
53
SM8C+
SM7A+
SM6A-
SM4B+
SM8 D+ E-
Q41
P39
SM5E
SM0C+
SM3B
SM7 + .1M
M7A
09
36
(27) = *
POT Q30
SM5A+
-100r
+100r
11
Q11
TO COC
-100TR
P24
66
SM2B
SM8 IN
SM8D
SM7B
SM5A
SM4A
SM5B
SM5D
SM0D
SM4B
SM9 + .1M
M8A

[redacted]



MOMENT EQUATIONS
RANGE & RANGE RATES
REPORT: LED570-1
DATE: 4 MARCH 1963

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APPENDIX NO. IX

ANALOG COMPUTER PARAMETER SHEETS

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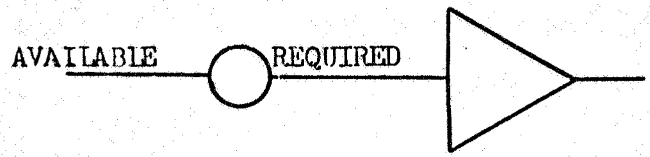

FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
P00	$1/K_{R0}$	.5	.5 [✓]
P01	$1/T_F$	$\frac{1}{.04} = 25$	[ ]
P02	100Ω/1100	.182	.182 [ ]
P03	100Ω/1100	.182	.182 [ ]
P04	$K_R\psi$	.5	.5 [✓]
P05	k_1	.2	.2 [✓]
P06	$1/T_f$	$\frac{1}{.04} = 25$	[ ]
P07	K_c		[ ]
P08	K_c		[ ]
P09	$1/T_F$	$\frac{1}{.04} = 25$	[ ]

[redacted]

[redacted]

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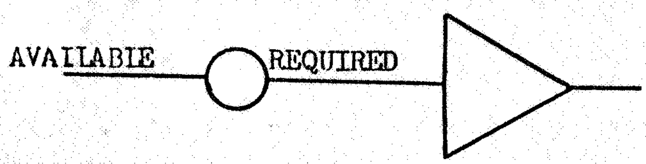
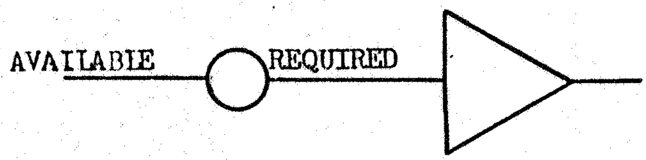


FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
P10	100m/100		.182 [ ]
P11	100m/100		.182 [ ]
P12	BIAS FOR COMP M5		[ ]
P13	BIAS FOR COMP. M0		[ ]
P14	BIAS FOR COMP. M6		[ ]
P15	$\frac{800\,\delta_\theta \text{ I.C.}}{100}$		.6975 [IC]
P16	$\frac{\frac{\theta}{2}\text{ IC}}{100}$		.075 [IC]
P17	$\frac{\psi/2 \text{ I.C.}}{100}$		.150 [IC]
P18	$\frac{\frac{\phi}{20}\text{ IC}}{100}$		.010 [IC]
P19	✓		[ ]

[redacted]

[redacted]



FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
P20	$\frac{b}{400}$	$\frac{20}{400} = .05$	.05 [1]
P21	$\frac{b}{400}$	$\frac{20}{400} = .05$	.05 [1]
P22	$\frac{-100 p_{IC}}{-100}$		.50 [IC]
P23	$\frac{-100 q_{IC}}{-100}$		.60 [IC]
P24	$\frac{-100 r_{IC}}{100}$		.40 [IC]
P25	$\frac{b}{400}$	$\frac{20}{400} = .05$	.05 [1]
P26	$100n/100$		.182 [1]
P27	$\frac{b}{400}$	$\frac{20}{400} = .05$	.05 [1]
P28			[ ]
P29			[ ]

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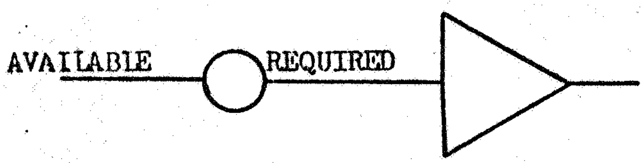

FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
P30			[ ]
P31			[ ]
P32	$\frac{-u_{IC}}{-100}$	$\frac{20}{100}$	.2 [IC]
P33	$\frac{-v_{IC}}{-100}$	$\frac{25}{100}$	.25 [IC]
P34	$\frac{-w_{IC}}{-100}$	$\frac{15}{100}$	.15 [IC]
P35	$\frac{\frac{T_m}{5000}}{\frac{T_m}{200}}$	$\frac{200}{5000} = .04$	.040 [1]
P36	100n/100		.182 [1]
P37	SCALING FOR MAIN THRUST		[ ]
P38	$\frac{-gl_1}{-100l_1}$	$\frac{g}{100} = \frac{(5.3154)}{100} = .0532$	.052 [1]
P39	$\frac{1\frac{T_m}{m}}{2.5\frac{T_m}{m}}$	$\frac{1}{2.5} = .04$	.04 [10]

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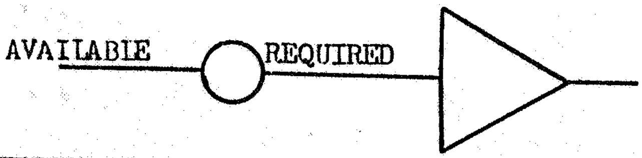

FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
P40	✓		[ ]
P41			[ ]
P42			[ ]
P43			[ ]
P44			[ ]
P45	.05		.05 [✓]
P46	$\frac{-9n_1}{-100n_1}$	$\frac{9}{100} = .0532$	.0532 [✓]
P47	.05		.05 [✓]
P48	$\frac{-9m_1}{-100m_1}$	$\frac{9}{100} = .0532$	0532 [✓]
P49	.5	.5	.5 [✓]

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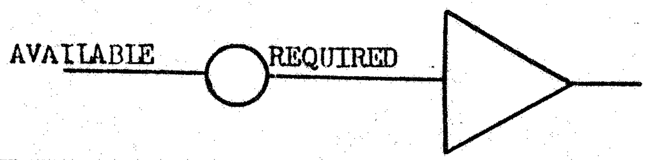
[redacted]



FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
Q00	$K_{R\phi}$	.5	.5 [/]
Q01	$1/T_f$	$\frac{1}{.04} = 25$	[ ]
Q02	DEAD ZONE FOR θ_c		[ ]
Q03	$1/T_f$	$\frac{1}{.04} = 25$	[ ]
Q04	$1/T_f$	$\frac{1}{.04} = 25$	[ ]
Q05	k_2	.1	.1 [/]
Q06	$\frac{100n}{100}$		.182 [1]
Q07	$\frac{100n}{100}$		.182 [1]
Q08	K_c		[ ]
Q09	D.Z. FOR θ_c		[ ]

[redacted]

L

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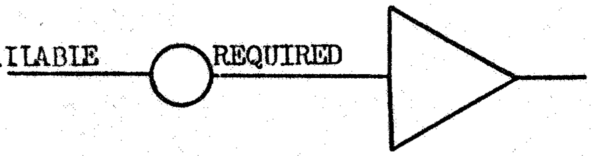
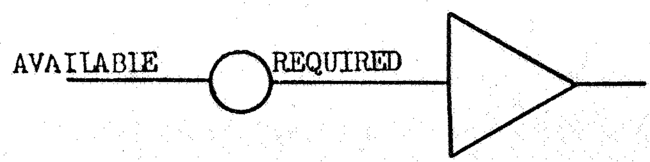
AVAILABLE  REQUIRED

FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

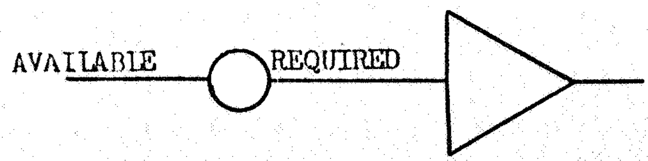
POT	FORMULA	CALCULATION	VALUE
Q10	$\frac{100 q_c}{\text{MAX. INPUT VOLTAGE}}$	$100\left(\frac{10}{57.3}\right)$	[ ]
Q11	$\frac{100 p_c}{\text{MAX. INPUT VOLTAGE}}$	$100\left(\frac{10}{57.3}\right)$	[ ]
Q12	$\frac{100 r_c}{\text{MAX INPUT VOLTAGE}}$	$100\left(\frac{10}{57.3}\right)$	[ ]
Q13	$1/T_f$	$\frac{1}{.04} = 25$	[ ]
Q14			[ ]
Q15			[ ]
Q16			[ ]
Q17	DEAD ZONE FOR ϕ_c		[ ]
Q18	DEAD ZONE FOR θ_c		[ ]
Q19	DEAD ZONE FOR ϕ_c		[ ]

[redacted]



FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
Q20	$\frac{T_{jq\,max}}{400}$	$\frac{200}{400} = .5$	.5 [1]
Q21	$\frac{T_{jq\,max}}{400}$	$\frac{200}{400} = .5$	.500 [1]
Q22			[ ]
Q23			[ ]
Q24			[ ]
Q25	$\frac{T_{jp\,max}}{400}$	$\frac{200}{400} = .5$	.5 [1]
Q26			[ ]
Q27	$\frac{T_{jp\,max}}{4000}$	$\frac{200}{4000} = .05$	.05 [10]
Q28	DEAD ZONE FOR 4c		[ ]
Q29	DEAD ZONE FOR 4c		[ ]



FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
Q30	$\dfrac{-\dot{\theta}/2\ (\text{DEG/SEC})}{-50\dot{\theta}\ (\text{RAD/SEC})}$	$\dfrac{57.3}{100}$ = .573	.573 [/]
Q31	$\dfrac{-\dot{\phi}/20\ (\text{DEG/SEC})}{-50\dot{\phi}\ (\text{RAD/SEC}}$.	$\dfrac{57.3}{1000}$	.0573 [/]
Q32	✓		[ ]
Q33	✓		[ ]
Q34	✓		[ ]
Q35	$\dfrac{-\dot{\psi}/2\ (\text{DEG/SEC})}{-50\dot{\psi}\ (\text{RAD/SEC})}$	$\dfrac{57.3}{100}$	.573 [/]
Q36	✓		[ ]
Q37			[ ]
Q38			[ ]
Q39			[ ]

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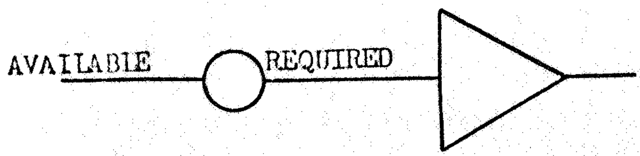
[redacted] RED



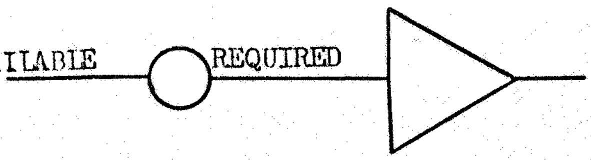
FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
P00	$\frac{T_{ff}/10}{T_{ff}/4}$	.4	.4 [1]
P01	$\frac{200\ gm}{250\ gm}$	8 = .8×10	.8 [10]
P02	$\frac{T_{ff}/10}{T_{ff}/4}$	.4	.4 [1]
P03	.577		.577 [2]
P04			[ ]
P05			[ ]
P06	$\frac{I_{440}}{100}$	6185×10^{-4} = .6185	.6185 [1]
P0[illegible]	[illegible]	.05([illegible]) [illegible]	[illegible] [1]
1	$\frac{.04\,T_{[illegible]}}{100}$	$\frac{(.04)([illegible])}{100}$ = .0[illegible]	.0[illegible] [1]
P0[illegible]			[1]

[redacted]

REPORT: LED570-1
DATE: 4 March 1963

[redacted]RED

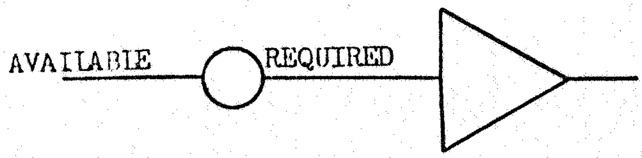
AVAILABLE  REQUIRED

FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
P10	.25		.25 [✓]
P11	$\frac{20\,T_{ij}/C_j}{T_{ij}/4}$	$\frac{80}{C_j} = \frac{80}{9660} = .0083$	.0083 [✓]
P12	$\frac{.04\,T_{ij}}{100}$	$\frac{.04(200)}{100} = .08$	.08 [✓]
P13	$\frac{20\,T_{i3}/C_j}{T_{i3}/10}$	$\frac{200}{C_j} = \frac{200}{9660} = .0207$	.0207 [✓]
P14	$\frac{20\,T_{ij}/C_j}{T_{ij}/4}$	$\frac{80}{C_j} = \frac{80}{9660} = .0083$	.0083 [ ]
P15	$\frac{-m_0/5}{-100}$	$\frac{m_0}{500} = \frac{337}{500} = .674$	.674 [✓]
P16	$\frac{20\,T_{ij}/C_j}{T_{ij}/4}$	$\frac{80}{C_j} = \frac{80}{9660}$	.0083 [✓]
P17	$\frac{-m_0/5}{-100}$	$\frac{m_0}{500} = \frac{337}{500} = .674$	-.674 [✓]
P18	$\frac{-2(X_{T_{n1}} - X_{CG_0})}{+100}$	$-0.25(6.5-5.7) =$ [illegible]	.7[illegible] [ ]
P19	.2		.2 [✓]

[redacted]

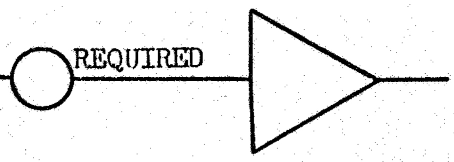
[redacted] RFD



FORMULA = REQUIRED / AVAILABLE

POT	FORMULA	CALCULATION	VALUE
P20	K_c		[ ]
P21	K_c		[ ]
P22	$\frac{I_x}{10} / 100$	$140 \times 10^{-3} = 0.14$	.14 [1]
P23	$\frac{-25(z_{Tm} - \bar{z}_{CG_0})}{+100}$	$-.025(0-.281) = .071$	.071 [1]
P24	$\frac{-25(y_{Tm} - \bar{y}_{CG_0})}{+100}$	$-.25(0-.025) = .00625$	[illegible] [ ]
P25	$\frac{I_{yz} q^2 / 10}{100 q^2}$	$I_{yz} \times 10^{-3} = 9493 \times 10^{-3} = 0.095$	[illegible] [1]
P26	$\frac{-I_{yz} r^2 / 10}{-100 r^2}$	same	[illegible] [1]
P27	$\frac{-I_{xy} p^2 / 10}{+100 p^2}$	$-I_{xy} \times 10^{-3} = 7821 \times 10^{-3} = [illegible]$	[illegible] [1]
P28	$\frac{T_{ip} C_{ip} / 10}{T_{ip} / 4}$	$\frac{4 C_{ip}}{10} = .4(5) = 2$	.2 [10]
P29	$\frac{I_{xy} p^2 / 10}{-100 q^2}$	$-I_{xy} \times 10^{-3} = 7821 \times 10^{-3} = [illegible]$	[illegible] [1]

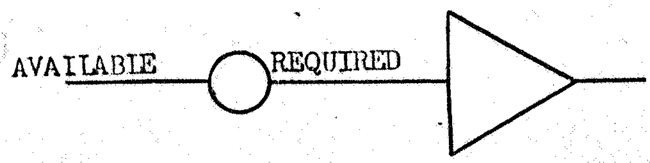
[redacted] RFD

AVAILABLE  REQUIRED

FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
P30	$\frac{-\frac{I_{yz}}{10} pq}{-100 pq}$	$I_{yz} \times 10^{-3} = 94.92 \times 10^{-3} = .0095$	.095 [/]
P31	$100\dot{\omega}/100$		.182 [/]
P32	/		[ ]
P33	$\frac{\frac{I_{yz}}{10} pr}{100 pr}$	$I_{yz} \times 10^{-3} = 94.92 \times 10^{-3} = .094$	.094 [/]
P34	$\frac{-\frac{4}{100} T_m \delta_\theta}{-\frac{4}{10} T_m \delta_\theta}$	.1	.1 [/]
P35	.4		[ ]
P36	$\frac{+\frac{I_{xy}}{10} p^2}{-100 p^2}$	$-I_{xy} \times 10^{-3} = 78.21 \times 10^{-3} = .078$	.078 [/]
P37	$\frac{-\frac{I_{xy}}{10} q^2}{+100 q^2}$	$-I_{xy} \times 10^{-3} = 78.21 \times 10^{-3} = .078$	.0782 [/]
P38	$\frac{\frac{I_{xx_0}}{100}}{100}$	$\frac{I_{xx_0}}{10^4} = 5862 \times 10^{-4} = .5862$	.5862 [/]
P39	$\frac{\frac{I_{yz}}{10} q\theta}{100 q\theta}$	$I_{yz} \times 10^{-3} = 94.92 \times 10^{-3} = .094$	.094 [/]

[redacted] RED

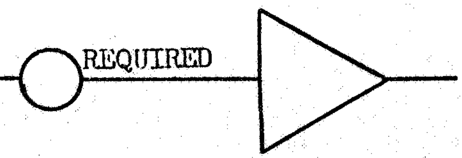


FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
P40	$100M/100$		.100 [1]
P41	$\frac{T_{j_{r\,max}}}{400}$	$\frac{200}{400} = .5$	.5 [1]
P42	$\frac{b}{400}$	$\frac{20}{400} = .05$	.05 [1]
P43	$\frac{-\frac{1}{100} T_m d\psi}{-\frac{4}{10} T_m d\psi}$	.1	.1 [1]
P44	.25		.25 [POT P44]
P45	✓		[ ]
P46	.2		.2 [1]
P47	$\frac{-\frac{I_{330}}{100}}{-100}$	$I_{330} \times 10^{-4} = 6370 \times 10^{-4} = .6370$	.6370 [1]
P48	$\frac{\frac{\partial I_{yy}}{\partial m}\frac{\Delta m}{10}}{\frac{\Delta m}{5}}$	$\frac{\frac{\partial I_{yy}}{\partial m}}{2} = \frac{21.5}{2} = 10.75 = .9773 \times 11$	.9773 [11]
P49	$\frac{-\frac{I_{yy_0}}{10}}{-100}$	$I_{yy_0} \times 10^{-3} = 6185 \times 10^{-3} = 6.185$	.6185 [10]

[redacted]

[redacted] RED

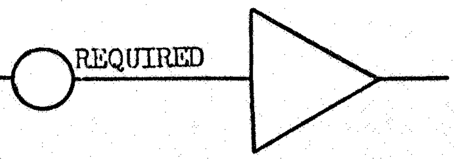
AVAILABLE  REQUIRED

FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
Q00	$\frac{800\delta_4 \, IC}{100}$		.6976 [IC]
Q01	$\frac{-T_{jx}/200}{-100}$	$\frac{200}{200(100)} = .01$	.01 [1]
Q02	✓		[ ]
Q03	✓		[ ]
Q04	$\frac{\frac{R_x - R_{xG}}{20} \, IC}{100}$		.500 [IC]
Q05	$\frac{100m}{100}$		.182 [$\frac{c}{op}$]
Q06	$\frac{R_y/20 \; IC}{100}$		.250 [IC]
Q07	$\frac{R_z/20 \; IC}{100}$		.400 [IC]
Q08	$\frac{-.08 \sin \theta_D}{+20 \sin R}$	$\frac{.08 \, \theta_D}{20} = \frac{.08(2.66)}{20} = .0106$	.0106 [1]
Q09	$\frac{100n}{100}$		.182 [$\frac{c}{op}$]

[redacted]

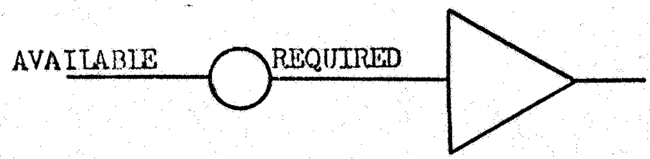
[redacted] RED

AVAILABLE  REQUIRED

FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
Q10	/		[ ]
Q11	/		[ ]
Q12	$\frac{+.08\,\dot{m}\,q\,\ell_D}{-20\,m\,\dot{q}}$	$\frac{-(.08)\ell_D}{20} = \frac{(.08)(2.66)}{20} = \overset{.0106}{.2128}$	.0106 [/]
Q13	$\frac{\frac{20\,T_m}{C_m}}{\frac{T_m}{200}}$	$\frac{4000}{C_m} = \frac{4000}{9350} = .$	.4278 [/]
Q14	$\frac{100\,m}{100}$		.192 [ ]
Q15	$\frac{-\dot{m}/5}{-20\dot{m}}$	.0100	.0100 [/]
Q16	/ $\frac{\frac{20\,T_{jx}}{C_j}}{\frac{T_{jx}}{10}}$	$\frac{200}{C_j} = \frac{200}{9660} = .0207$	.0207 [/]
Q17	/	$\frac{200}{C_j} = \frac{200}{9660} = .0207$	.0207 [/]
Q18	$\frac{-25\frac{dX_{CG}}{dm}\Delta m}{\frac{\Delta m}{5}}$	$-125\frac{dX_{CG}}{dm} = -125(-.0107) = +$[illegible]	[illegible] [/]
Q19	$\frac{100\,m}{100}$		.192 [ ]

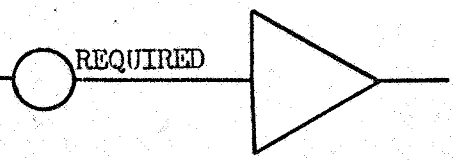
[redacted]



FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
Q20	k_2		.1 [1]
Q21	Kc		[ ]
Q22	$\frac{\frac{\partial I_{xz}}{\partial m}\frac{\Delta m}{10}}{\frac{\Delta m}{5}}$	$.5\frac{\partial I_{xz}}{\partial m} = .5(1.01) = .505$	.505 [1]
Q23	$\frac{-25\frac{\partial \bar{z}_{CG}}{\partial m}\Delta m}{\Delta m/5}$	$-125\frac{\partial \bar{z}_{CG}}{\partial m} = -125(-.0013) = .1625$	.1625 [1]
Q24	$\frac{100n}{100}$		.182 [illegible]
Q25	$\frac{-25\frac{\partial \bar{y}_{CG}}{\partial m}\Delta m}{\Delta m/5}$	$-125\frac{\partial \bar{y}_{CG}}{\partial m} = -125(-.000325) = .0407$	.0407 [1]
Q26	$\frac{\frac{I_{xy}}{10}\dot{q}}{-100\dot{q}}$	$-I_{xy}\times10^{-3} = 78.21\times10^{-3} = .078$	.0782 [1]
Q27	$\frac{\frac{p\dot{m}l_{pe}^2}{10}}{20\dot{p}\dot{m}}$	$\frac{l_{pe}^2}{200} = \frac{15.3}{200} = .0765$	.0765 [1]
Q28	$\frac{\frac{I_{xy}}{10}\dot{p}}{-100\dot{p}}$	$-I_{xy}\times10^{-3} = 78.21\times10^{-3} = .078$	[illegible] [1]
Q29	$\frac{100n}{100}$		.182 [illegible]

[redacted] RED

AVAILABLE  REQUIRED

FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
Q30	$\frac{I_{y3}\dot{r}/10}{100\dot{r}}$	$I_{yy}\times10^{-3} = 94.92\times10^{-3} = .095$	[illegible] [1]
Q31	$\frac{9\dot{m}\,l_{0zz}^2/10}{-20\,9\dot{m}}$	$\frac{-l_{0zz}^2}{200} = \frac{304}{200} = .152$	.152 [1]
Q32	$\frac{T_{j9}\,l_{j9}/10}{T_{j9}/4}$	$\frac{4}{10}l_{j9} = .4(5.5) = 2.2$	.22 [10]
Q33	$\frac{T_{jr}\,l_{jr}/10}{T_{jr}/4}$	$\frac{4}{10}l_{jr} = .4(5.5) = 2.20$	.22 [10]
Q34	$\frac{100n}{100}$		.182 [1]
Q35			[ ]
Q36	k_1		.2 [1]
Q37	$\frac{r\dot{m}\,l_{0qr}^2/10}{20r\dot{m}}$	$\frac{-l_{0qr}^2}{200} = \frac{30.4}{200} = .152$	.152 [1]
Q38	$\frac{\frac{dI_{xx}}{dm}\frac{\Delta m}{100}}{\frac{\Delta m}{5}}$	$.05(17.5) = .875$	.875 [1]
Q39	$\frac{100n}{100}$		.182 [illegible]

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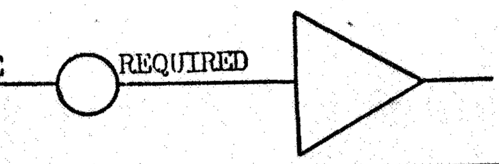
AVAILABLE REQUIRED



FORMULA = $\frac{\text{REQUIRED}}{\text{AVAILABLE}}$

POT	FORMULA	CALCULATION	VALUE
Q40	$\frac{b}{400}$	$\frac{20}{400} = .05$	.05 [1]
Q41	$\frac{T_{n\,max}}{400}$	$\frac{200}{400} = .5$	.5 [1]
Q42			[ ]
Q43	.25		.25 [P40]
Q44	.2		.2 [ ]
Q45	$\frac{-200 z_n}{-25 z_n}$	$8 = .8 \times 10$	.8 [10]
Q46	1		[ ]
Q47	$\frac{\frac{\partial I_{33}}{\partial m}\frac{\Delta m}{100}}{\frac{\Delta m}{5}}$	$.05(20.8) = 1.04 = .104 \times 10$	.104 [10]
Q48	$\frac{\frac{I_{yy_0}}{100}}{10}$	$I_{yy_0} \times 10^{-3} = 6155 \times 10^{-3} = 6.155$	.6155 [10]
Q49	$\frac{\frac{\partial I_{yy}}{\partial m}\frac{\Delta m}{10}}{\frac{\Delta m}{5}}$	$.5(21.5) = 10.75 = .9773 \times 11$	.9773 [11]

APPENDIX NO. X

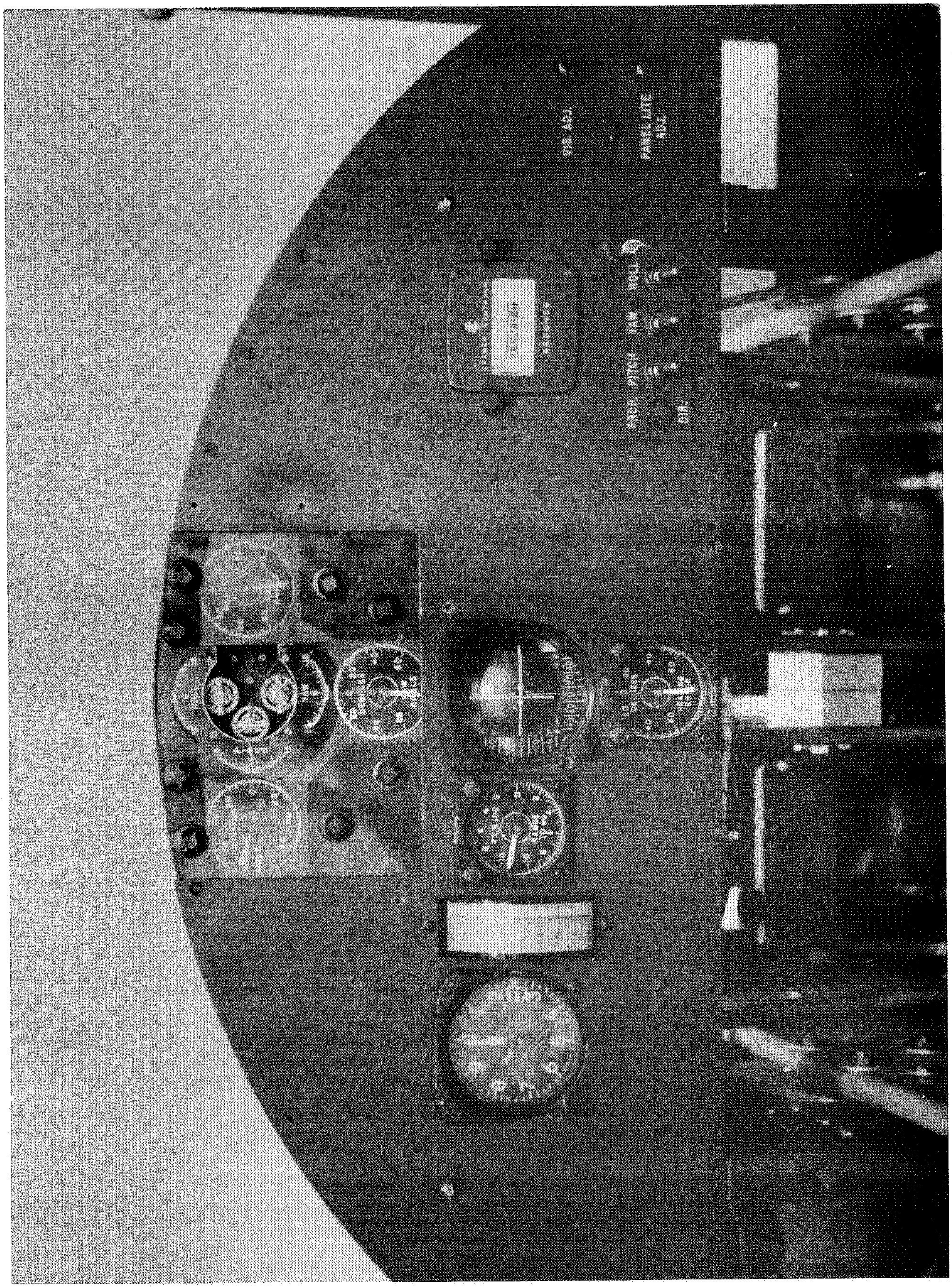
PHOTOGRAPHS OF THE HOVER AND LANDING SIMULATOR

a) Instrument Panel

b) Cockpit Layout

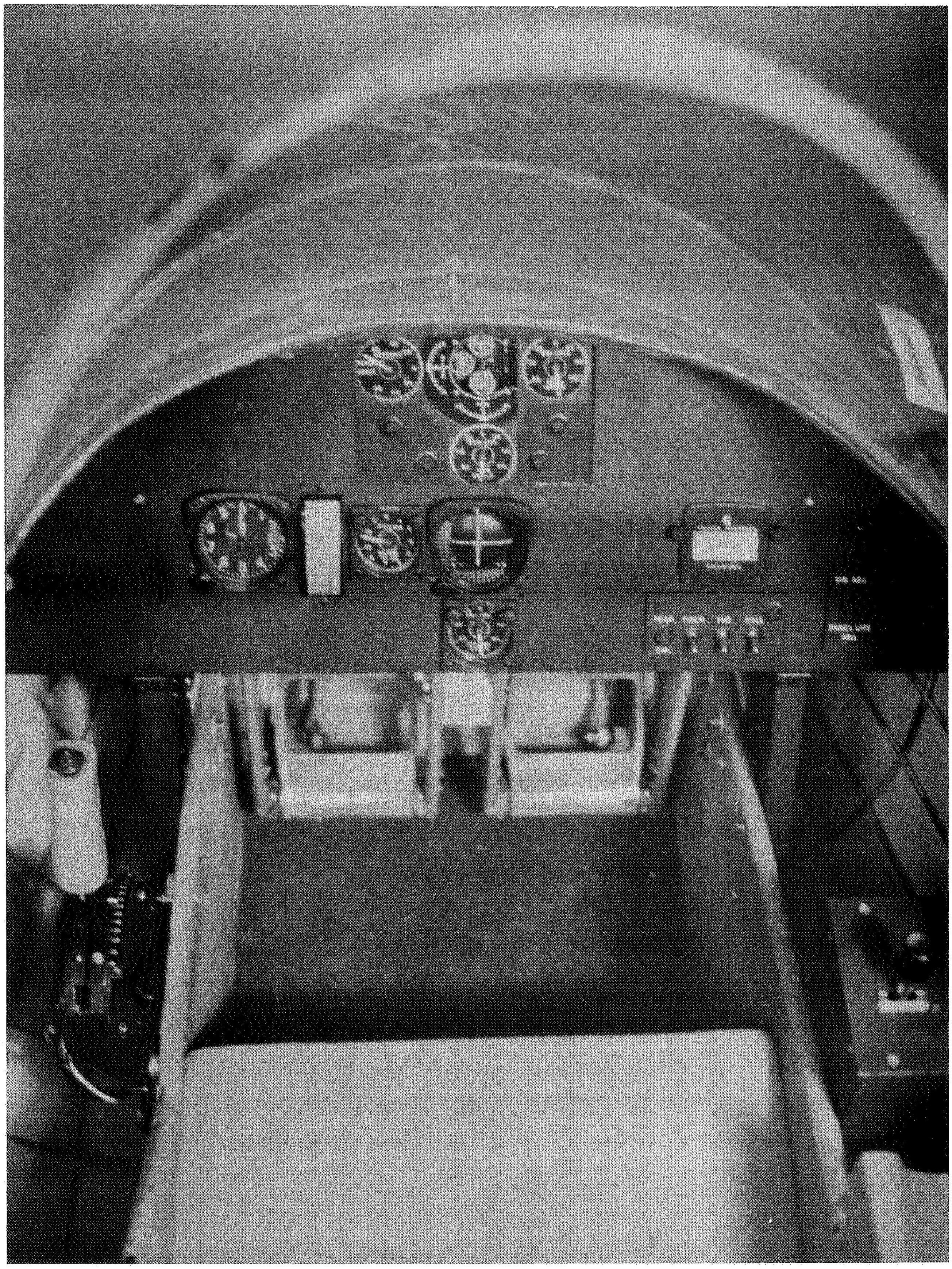
c) Analog Computers

CONFIDENTIAL



Landing Simulator Display Panel

CONFIDENTIAL



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Landing Simulator Cockpit

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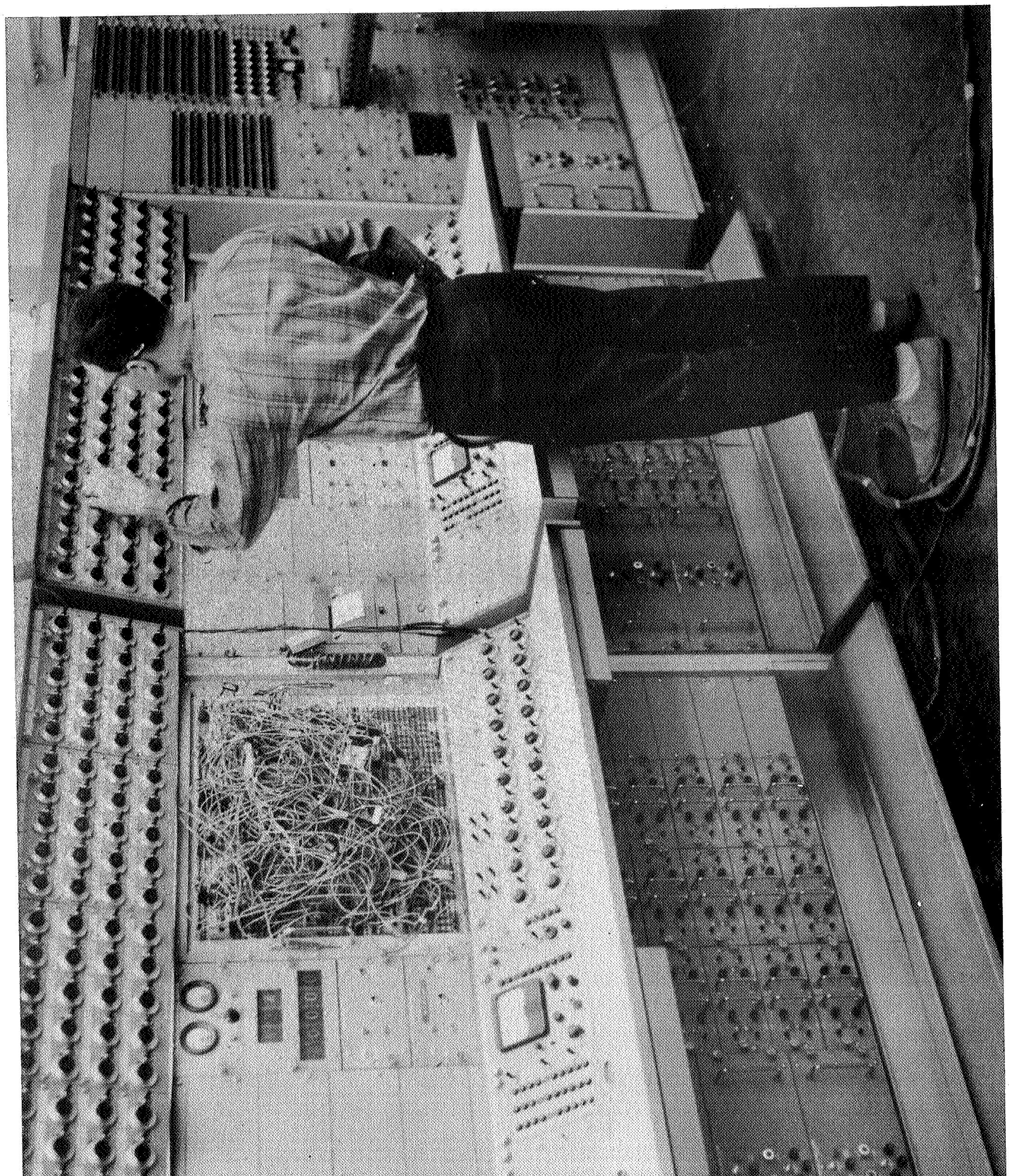


Analog Computers

CONFIDENTIAL

APPENDIX NO. XI

COMPARISON OF LEM FLIGHT CONTROL SYSTEM AND FLIGHT CONTROL SYSTEM USED FOR LUNAR LANDING SIMULATION

APPENDIX NO. XI

COMPARISON OF LEM FLIGHT CONTROL SYSTEMS AND FLIGHT CONTROL SYSTEMS USED FOR LUNAR LANDING SIMULATION

In order to reduce the amount of analog computer equipment required for the Phase A landing simulation certain simplifications of the flight control system were made. These simplifications will retain the fundamental dynamic behavior of the control system as felt by the pilot. The major simplifications of the flight control system for simulation purposes are:

a) Use of a linearized control modulation function which approximates the time-average thrust level obtained from the jets with a pulse modulation system.
b) Simplified RCS Command logic
c) Simplified jet dynamics using analog computer relay delay times to approximate actual on-off delay times, and thrust rise and decay times.

In order to show the discrete differences between the actual LEM Flight Control system and that in the landing simulation it will be necessary to review both in detail. The following sections will be devoted to presenting each system in terms of descriptions and also by schematic presentations.

I. Preliminary Description of Control Electronics Section of Stabilization and Control Subsystem.

The following description represents a preliminary system, many of the concepts mentioned below are subject to change as the various analytical and simulator studies progress. At the time of this report, the below described Stabilization and Control Subsystem was being used as the model for the simplified flight control system incorporated in the landing simulation.

A. General: The Stabilization and Control Subsystem is divided into two sections, the Control Electronics Section (CES) and the Backup Guidance Section (BGS). This discussion concerns only the Control Electronics Section.

B. Description: Figure 1 is a block diagram of the Control Electronics Section of the S and C Subsystem. To simplify the diagram, only one control channel is shown (pitch or yaw). The roll control channel would be identical except for the automatic trim and the Attitude Command Mode. As shown the Control Electronics Section consists of four assemblies; the Guidance Coupler Assembly, the Attitude and Translation Control Assembly, the Rate Gyro Assembly, and the Descent Engine Control Assembly. Pilot inputs are derived from the Attitude Controller and the Thrust Controller as shown.

1. Guidance Coupler Assembly - The Guidance Coupler Assembly contains the mode switching for both attitude and translational control.

2. Rate Gyro Assembly - This assembly contains the rate sensors and associated electronics for each of the three axes. To increase reliability, a triple redundant system is presently under consideration. This system uses three gyros per axis and a majority voting technique.

3. Attitude and Translation Control Assembly - This assembly controls the firing of the reaction jets and provides automatic trim signals for the gimballed descent engine. It provides the necessary signal conditioning, gain control, limiting, etc., to all command and feedback signals.

   (a) Dead-band - As shown in figure 1, each channel has an adjustable dead band on the attitude error input. This adjustment will probably be a two level device, a large dead band (say $\pm 5^{\circ}$) for coasting period limit cycles where fuel economy is paramount and a narrow dead band (say $\pm 0.1^{\circ}$) for periods of main engine thrusting. One switch will control the dead band in all three axes.

   (b) Limiter - Figure 1 shows a limiter following the dead band on the attitude error signal. The purpose of this limiter is to limit the rate at which the vehicle can change attitude and thereby conserve fuel.

   (c) Logic - The logic selects the proper reaction jets for attitude control. The proposed 45° rotation from the principal axes for the jets provides complete redundancy in each axis for attitude control. If any quad of jets was truned off for any reason, the logic would still select the proper jets to enable firing couples at all times for attitude control. The logic would also "shut off both" rather than "fire both" of any opposed jets during periods of both attitude and translational control.

   (d) Pulse Generator - The pulse modulation scheme currently under consideration is a pulse ratio modulation scheme which essentially consists of frequency modulation for small inputs and then pulse width modulation for larger inputs. In the Emergency Attitude mode, and for translational control the pulse generator will provide either a single minimum impulse command or a low frequency series of minimum impulses.

   (e) Auto trim signal - As shown, the same signal that goes to the pulse generator for firing the jets also is used to drive the gimballed descent engine. Interlocks are provided so that the auto trim operates only when the engine is firing.

4. Descent Engine Control Assembly - This assembly contains the throttle servo and the gimbal drive mechanism for the descent engine.

   (a) Throttle Control - As shown in figure 1, the throttle servo is a position servo which positions the throttle proportional to the electrical input signal. This input signal comes from the Navigation and Guidance Subsystem during automatic control. During hover and landing the pilot positions the throttle through his thrust controller. Methods of acceleration control rather than thrust control are currently under consideration.

   (b) Gimbal Drive System - The gimballed descent engine is used for trim only. The drive motors are of a fixed slow speed screw-jack type to minimize power requirements. Automatic trim is of an open-loop type whereby the motor runs at its fixed speed whenever the input signal exceeds a threshold value. Other methods of automatic trim are also under consideration.

5. Attitude Controller - The attitude controller is a three-axis right hand controller. It contains a position potentiometer and a pair of detent switches in each axis. The potentiometer provides proportional rate commands in the Attitude Hold Mode or proportional attitude commands in the Attitude Command Mode (pitch and yaw only). The detent switches synchronize the attitude follow-up function in the Attitude Hold Mode or command jet firings in the Emergency Attitude Mode.

6. Thrust Controller - The thrust controller is a left-hand controller which contains a position potentiometer in one axis only, and a pair of detent switches in each of three axes. The potentiometer is used for proportional manual throttle control and the detent switches are used to fire the reaction jets for translational control.

C. Modes of Attitude Control: Four modes of attitude control are provided. Figure 2 through 5 shows simplified block diagrams of each.

1. Guidance Mode - The Guidance Mode is a fully automatic mode. Attitude error signals are sent to the S & C Subsystem from the Navigation and Guidance Subsystem or from the Backup Guidance Section. The attitude error signal is passed through the dead band and limiter and combined with the rate gyro damping signal as shown in figure 2. The resultant signal then controls the firing of the reaction jets through the logic and pulse generating circuits. This same signal (attitude error and rate) operates the gimbal drive motor for automatic trim when the descent engine is firing. The Guidance Mode provides fully automatic attitude control capabilities during all phases of the mission except hover, landing and docking.

2. Attitude Hold Mode - In the Attitude Hold Mode the pilot commands an angular rate proportional to displacement of the attitude controller. When the controller is in its neutral position, the vehicle will hold attitude.

   As shown in figure 3, when the controller is out of detent, the attitude loop is opened and the attitude synch. is in follow up. The potentiometer in the attitude controller is compared to the rate gyro, thereby providing a proportional rate command. When the controller is returned to detent, the rate command goes to zero and the attitude loop is closed.

   This mode is the primary attitude control mode during the docking phase of the mission. It would also be used anytime the pilot wished to reorient the vehicle during coasting flight.

3. Attitude Command Mode - In this mode the pilot commands attitude proportional to his attitude controller displacement. That is, when the pilot "tilts" the control stick, the vehicle tilts; when he lets go of the stick, the vehicle erects. This mode is used to translate during the hover and landing phases and is mechanized in the pitch and yaw axes only (roll remains in the Attitude Hold Mode). A procedure for translating while hovering would be:

   (a) Pilot rolls vehicle to line it up in the direction he wants to translate. (Roll in Attitude Hold Mode)

   (b) Pilot pitches forward linear acceleration proportional to pitch angle which in turn is proportional to pilot input.

   (c) Pilot centers control stick - vehicle erects and maintains constant linear velocity.

   (d) Pilot pitches in opposite direction to stop.

4. Emergency Attitude Mode - As the name implies this mode would be used only under emergency conditions. It provides the pilot only with open loop type acceleration control and is therefore selectable on an individual axis basis. The need for two types of emergency control is indicated; a minimum pulse control to provide the precision necessary for docking, and an on-off type full thrust control for rapid maneuvering (or unmaneuvering).

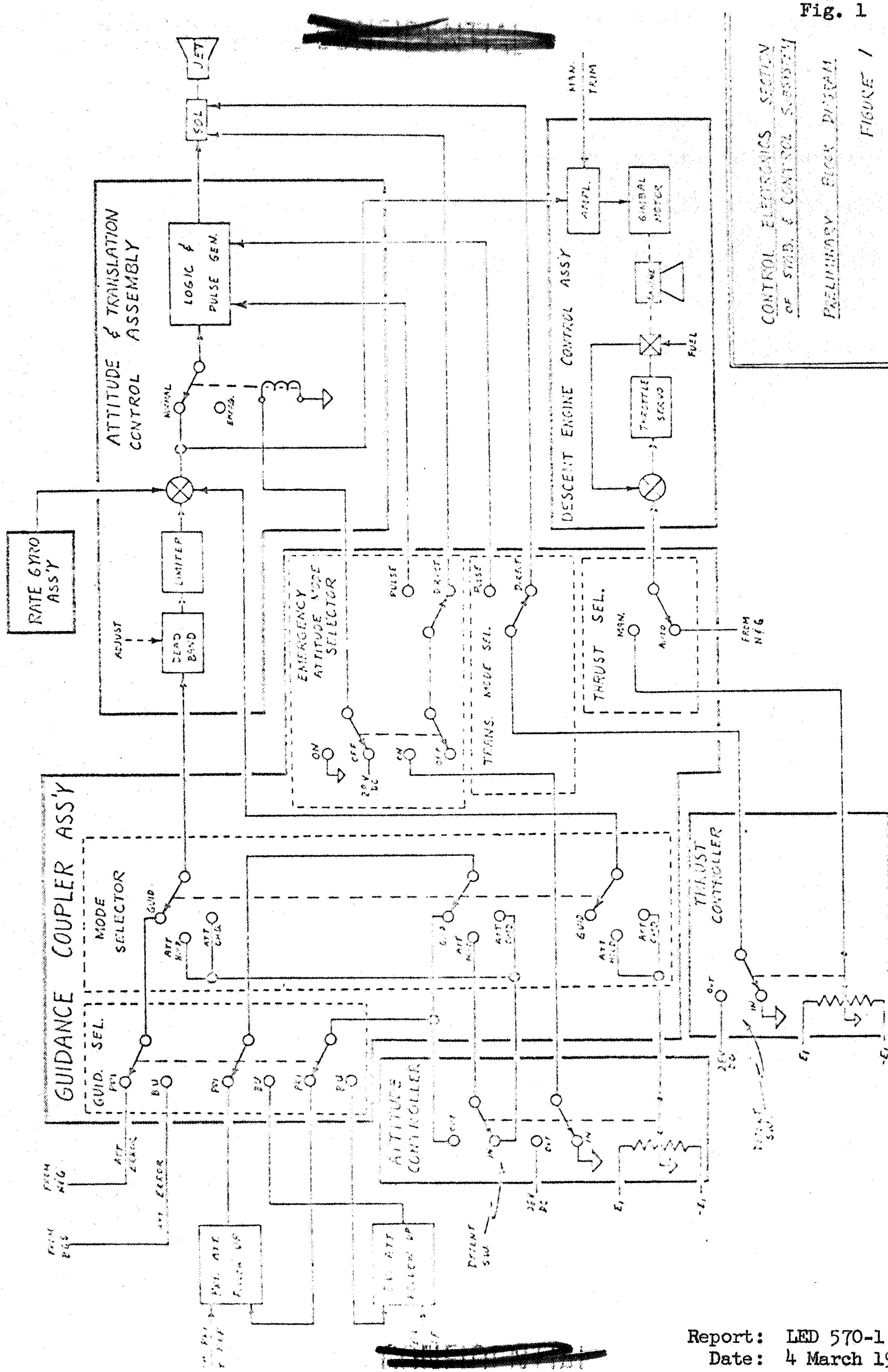
   As indicated in figures 1 and 5, the on-off type of control is called "direct" and the minimum pulse control is called "pulse". Several types of "pulse" control are under consideration; a "one-shot" type whereby one minimum impulse is commanded each time the attitude controller detent switch is operated; a "repeated pulse" type which commands repeated minimum impulses at a low frequency (less than 2/sec.) as long as the stick is out of detent; and a "proportional" type which utilizes the pot in the controller to command proportional pulse width (still at a low frequency).

D. Translational Control: The method of translational control is indicated in figure 1. Switches in the Thrust Controller are used to command jet firings in an open-loop fashion. As indicated either an on-off or pulse type of control could be selected similar to those of the Emergency Attitude Mode.

Translational control would be used during docking and possibly for small corrections during hover and landing.

E. Throttle Control: Figure 1 shows a throttle control servo for the engine which can accept either automatic or manual commands. Automatic control would be provided from the N and G Subsystem down to the hover point at which time the pilot would take over. Several types of control are currently under consideration. These include: throttle position control, thrust magnitude control, and acceleration control.

F. Gimballed Descent Engine Control: Studies are presently underway comparing a slow speed (trim only) gimbal drive system to a high speed (maneuvering) type. For either type the input would be the same signal that commands the reaction jet firings. For the trim only type a slow, fixed speed drive motor could be used in an open-loop fashion to command a fixed gimbal rate whenever the input exceeded a threshold value. Interlocks would be included to permit the automatic trim operation only when the engine is firing. Figure 1 also indicates manual trim capabilities.

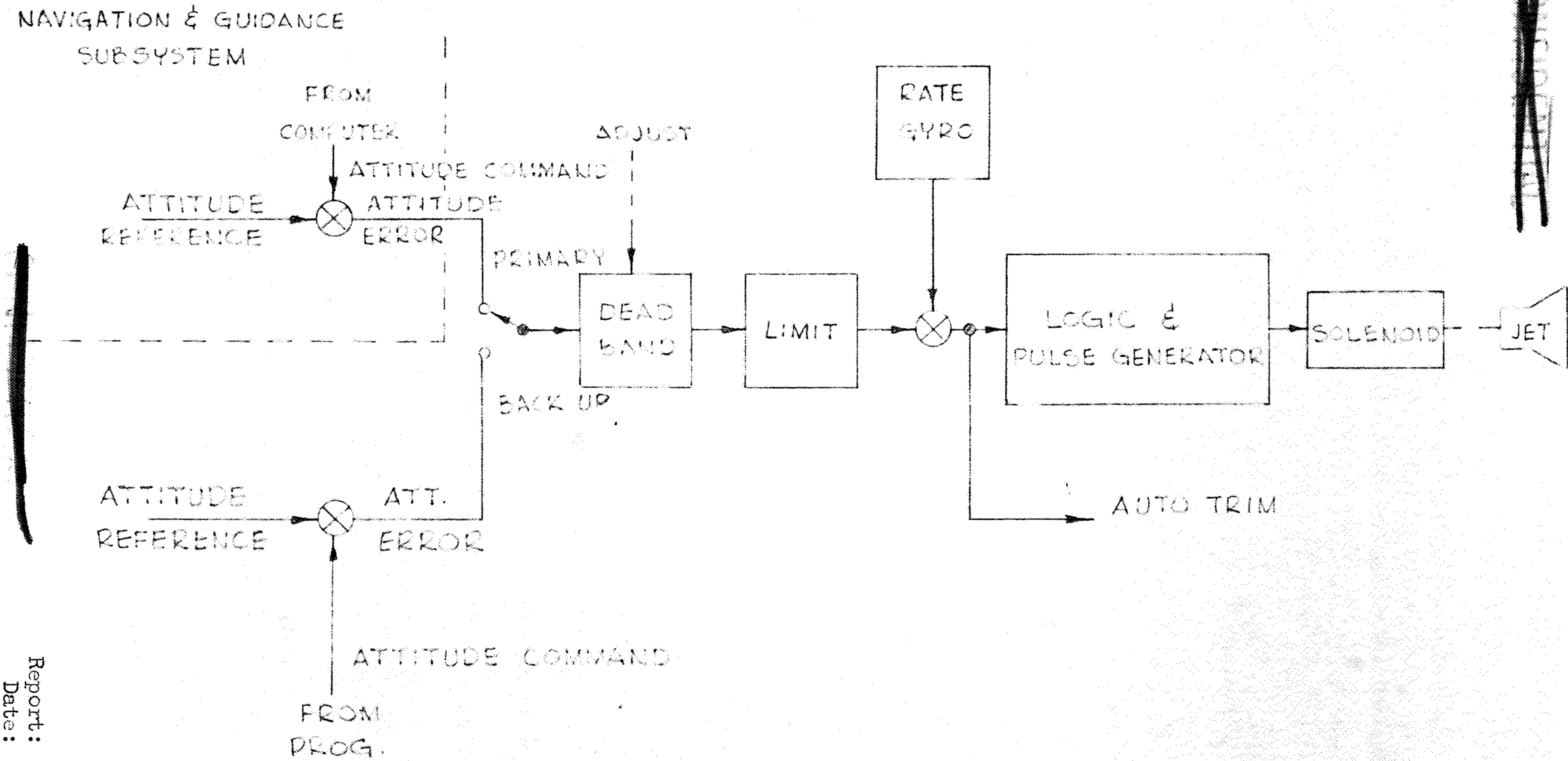

CONTROL ELECTRONICS SECTION OF STAB. & CONTROL SUBSYSTEM
PRELIMINARY BLOCK DIAGRAM
FIGURE 1
JET
SOL
ATTITUDE & TRANSLATION CONTROL ASSEMBLY
LOGIC & PULSE GEN.
NORMAL
EMERG.
LIMITER
DEAD BAND
ADJUST
RATE GYRO ASS'Y
DESCENT ENGINE CONTROL ASSY
AMPL.
GIMBAL MOTOR
ENGINE
THROTTLE SERVO
FUEL
MAN. TRIM
EMERGENCY ATTITUDE MODE SELECTOR
PULSE
DIRECT
ON
OFF
28V DC
TRANS. MODE SEL.
THRUST SEL.
MAN.
AUTO
FROM N&G
GUIDANCE COUPLER ASS'Y
MODE SELECTOR
GUID.
ATT HLD
ATT CMD
GUID. SEL.
PRI
BU
THRUST CONTROLLER
OUT
IN
28V DC
E1
-E1
ATTITUDE CONTROLLER
DETENT SW.
FROM N&G
ATT ERROR
PRI. ATT. FOLLOW UP

[redacted]

ATTITUDE CONTROL MODES

GUIDANCE MODE

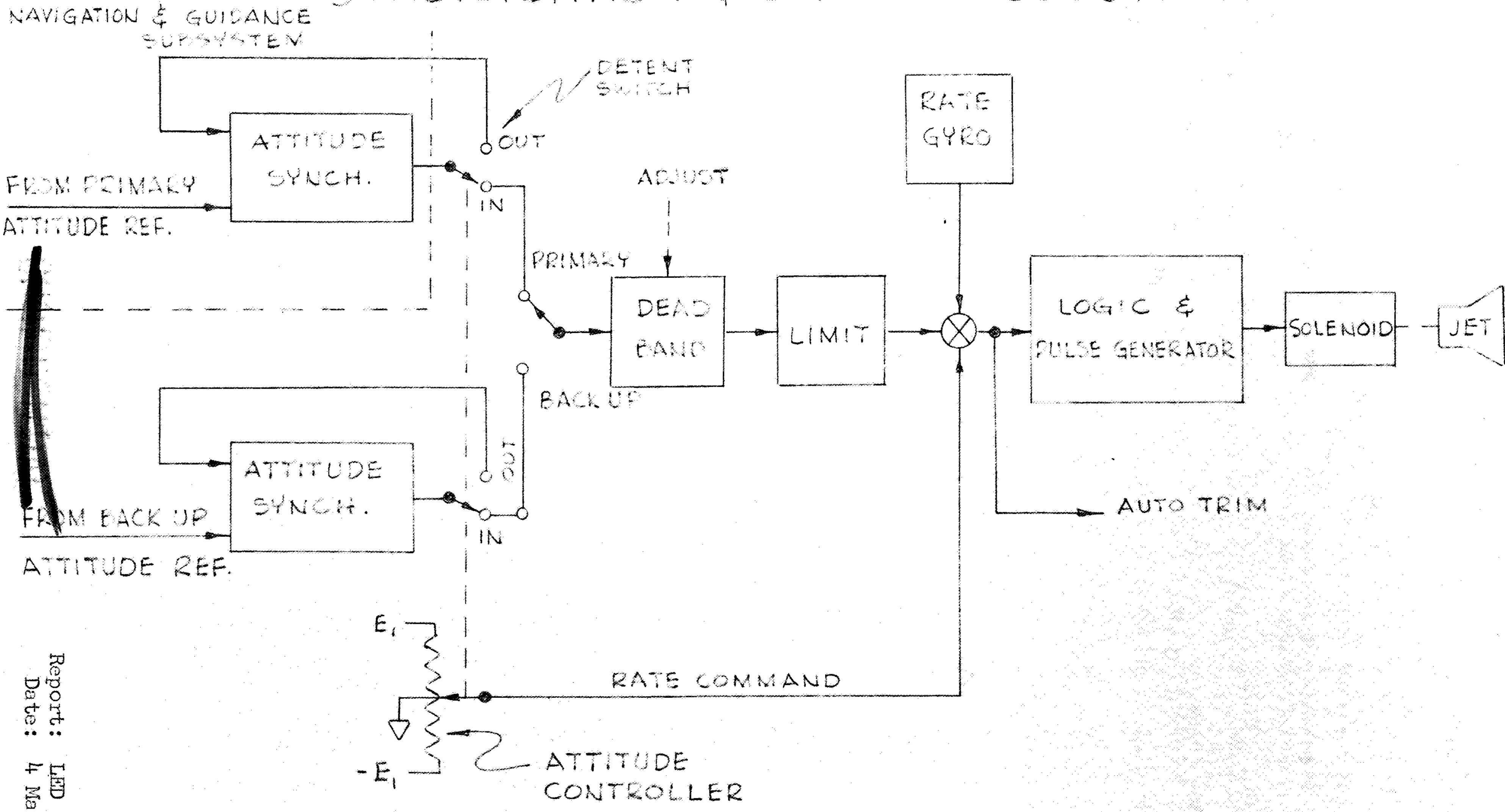
STABILIZATION & CONTROL SUBSYSTEM



ATTITUDE CONTROL MODES

ATTITUDE HOLD MODE

STABILIZATION & CONTROL SUBSYSTEM



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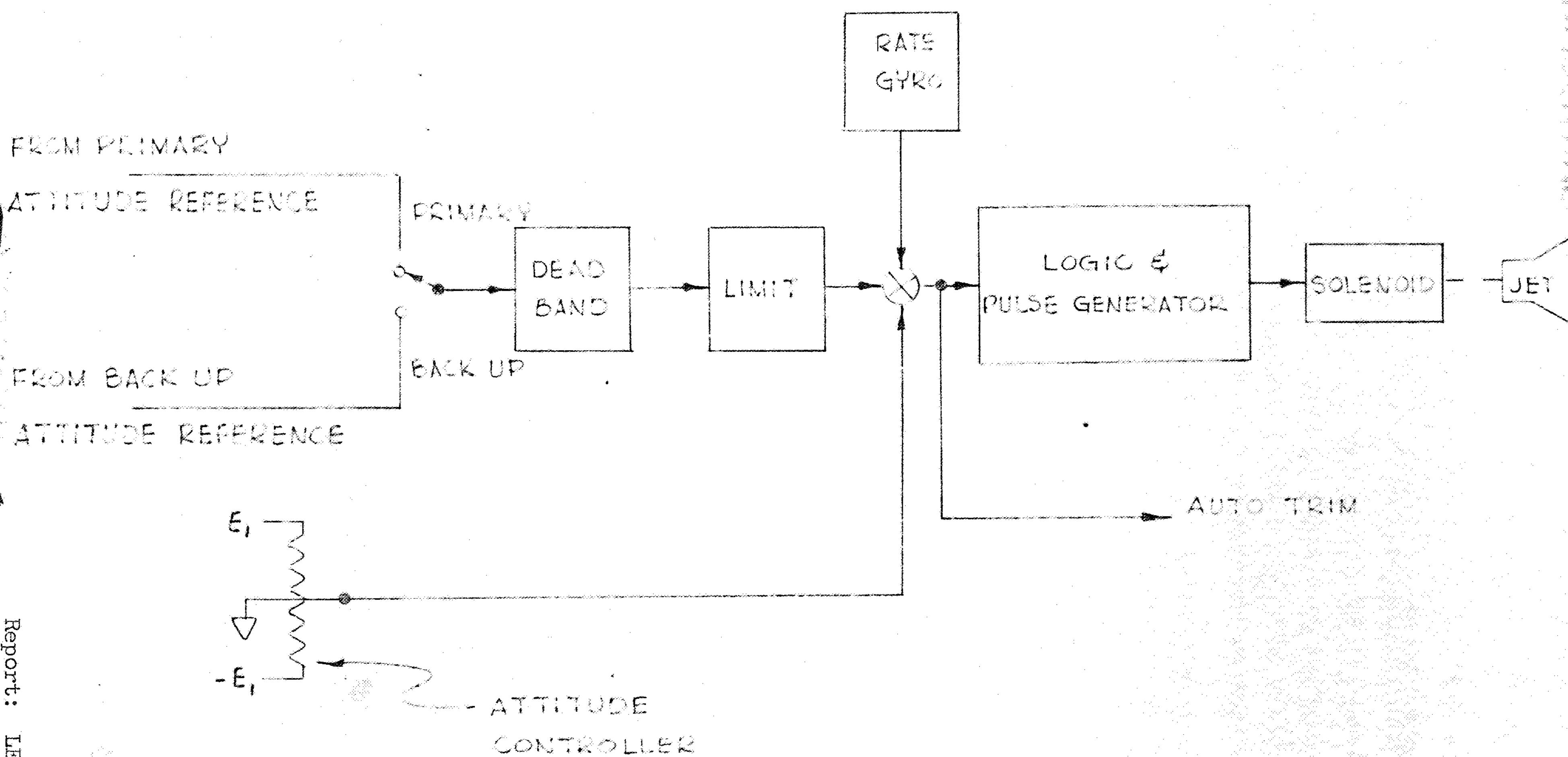
ATTITUDE CONTROL MODES

ATTITUDE COMMAND MODE

STABILIZATION & CONTROL SUBSYSTEM



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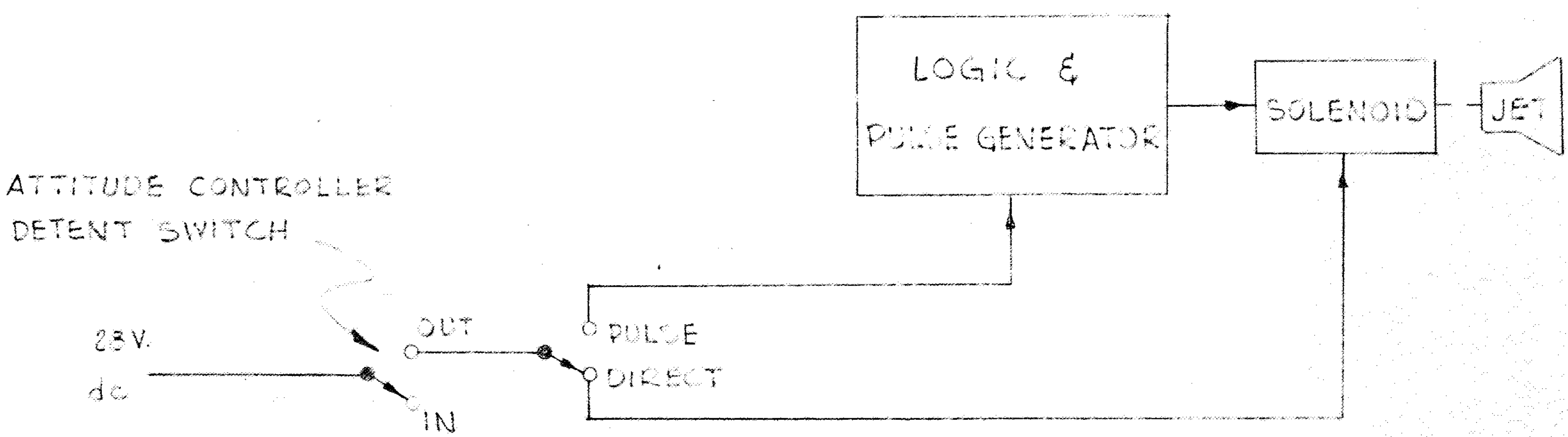
ATTITUDE CONTROL MODES

EMERGENCY ATTITUDE MODE

STABILIZATION & CONTROL SUBSYSTEM



II. Simplified Representation of the Flight Control System Dynamics for the Landing Simulation.

A highly schematic representation of the dynamics of the flight control system for use in the LEM landing simulation is presented in figures 6 and 7. These block diagrams will permit evaluation by the pilot of these three: fully proportional gimballed engine; trimmable engine plus reaction control system; reaction control system alone. In addition, it will permit evaluation of several modes of emergency operation.

The reaction control jets are used in an on-off fashion, and the time-lags adjusted to give proper limit cycles. Vehicle behavior in the rate augmented mode will appear substantially the same to the pilot whether on-off or a pulse modulation scheme is used.

A. General: The Flight Control System dynamics for the Phase A Lunar Landing Simulation have been simplified to reduce the amount of analog computer equipment required. The following description presents the simplified flight control system used in lieu of the complete Stabilization and Control Subsystem described in paragraph I. Major differences and/or simplifications will be pointed out.

B. Description: Figures 6 and 7 are the block diagrams of the simplified flight control system for the roll, pitch and yaw axes. As can be seen from figure 6, the gimballed descent engine may be used fixed, for automatic trim or for maneuvering with slight modification of gains. The pilot inputs are obtained from the Attitude Controller and the Descent Engine Thrust Controller as shown.

1. Attitude Control Provisions - Attitude control is provided primarily by the firing of the reaction jets. In addition provision has been made for the evaluation of a fully proportional gimballed descent engine for attitude control.

(a) Dead-band - Provision has been made for adjustment of time-lags to give proper limit cycles in the simulated system.

(b) Logic - A simplified logic has been devised for attitude control using the reaction jets. This logic is based on the present 45° location of the jets as shown on page 44. The actual LEM Reaction Control System Logic is shown on page 104, while the simplified command logic is shown on page 105. It should be noted that while provision has been provided for translation control along the Y and Z axes the actual vehicle logic is not used in the simplified system. It is assumed that translation control induces no moments and the forces act at the center of gravity.

(c) Pulse Generator - The pulse modulation scheme currently under consideration, consists of frequency modulation for small inputs and then pulse modulation for larger inputs. For the Landing Simulation, this scheme was simplified by using a linearized control modulation function approximating the time-average thrust levels obtained from the reaction jets. The reaction jet dynamics are simulated by using the analog computer relay delay times to simulate lags or delays. This simplification is considered valid as the delay time of the computer relays are approximately 10 milliseconds compared to the actual jet on-delay of 6 to 10 milliseconds (off-delay of same magnitude) and a thrust rise or decay time of approx. 2 to 3 milliseconds. For the emergency direct modes shown in figures 6 and 7 the pilot is given direct access to the reaction jets which will essentially operate in a "bang-bang" (full on-off) manner.

(d) Automatic Trim Signal - As shown, the same signal that goes to the reaction control system for firing the jets also is used to drive the gimballed descent engine.

(e) Proportional Gimballed Descent Engine - Provision has been made for readily adopting the simulation to the use of a proportional gimballed descent engine for attitude control in conjunction with the reaction control system.

2. Translation Control Provision - Provision has been made in the Lunar landing simulation for the evaluation of translation control using the reaction jets. The control logic has been modified for this evaluation such that only pure translational accelerations are experienced by the vehicle. This simplification is considered valid as translational control would probably be used during hover or landing while the vehicle is in the attitude command mode. Translational control is provided along the Y and Z axes only.

3. Attitude Controller - The attitude controller is a three-axis right hand fingertip controller. The yaw attitude is controlled by a left-right movement of the controller arm, the pitch attitude is controlled by fore and aft motion and roll attitude is controlled by a twist motion of the controller.

4. Thrust Controller - The thrust controller is a left hand controller which contains a position potentiometer in one axis only. The time constant chosen for thrust buildup to 65% of command at the low throttling range has been selected as .3 seconds. A modified trim detent switch has been provided at the top of the throttle and is used to fire the reaction jets for translational control.

C. Modes of Attitude Control: Two modes of attitude control are presently provided. Provision has also been made for a fully proportional gimballed descent engine for maneuvering.

1. Attitude Hold Mode - In the Attitude Hold Mode the pilot commands a rate proportional to displacement of the attitude controller. When the controller is in the neutral position, the rate command goes to zero, the attitude loop is closed and the vehicle will hold attitude.

2. Emergency Direct Mode - This mode provides the pilot with direct access to the reaction jets and results in an open loop type acceleration control. This mode is an on-off type full thrust control with no rate feedback or attitude hold feature.

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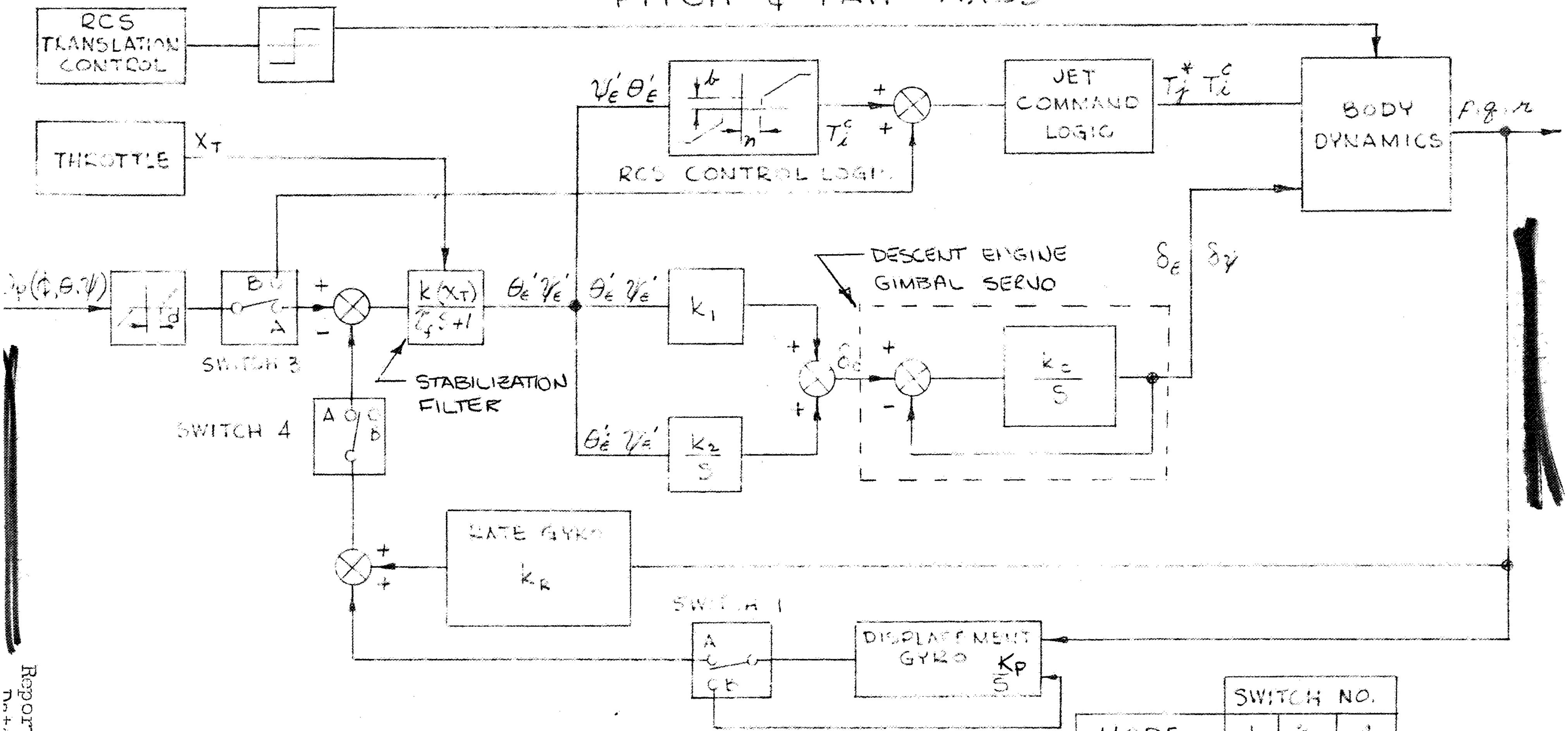
SIMPLIFIED FLIGHT CONTROL SYSTEM PHASE

A LANDING SIMULATION

PITCH & YAW AXES



MODE	SWITCH NO. 1	3	4
STAB. AUG.			
$\omega_p < d$	A	A	A
$\omega_p > d$	B	A	A
EMER. DIR.	B	B	B
ATT. COMM.	A	A	A

* REFER TO DS-C-1
& L300-MOS-7

[redacted]

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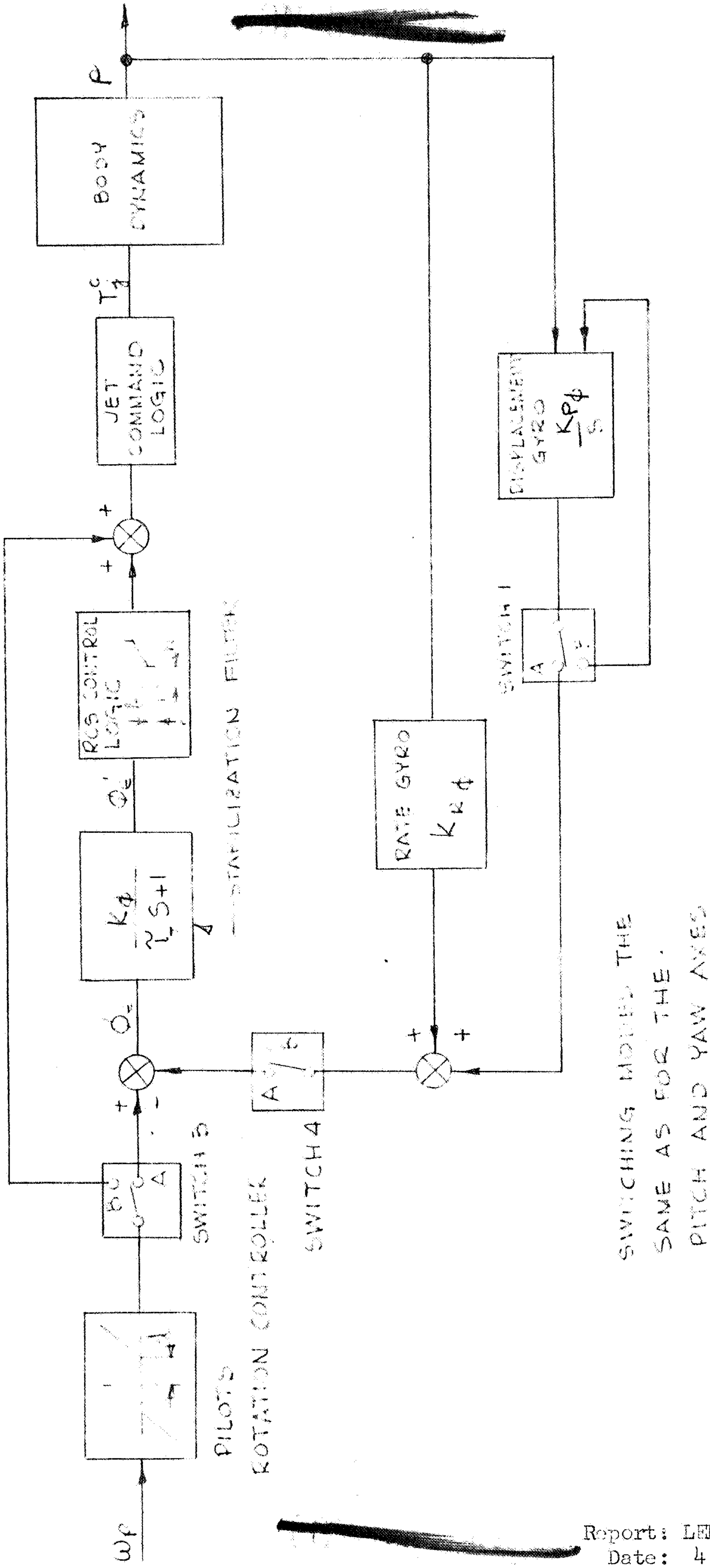
SIMPLIFIED FLIGHT CONTROL SYSTEM PHASE

A LANDING SIMULATION

ROLL AXIS



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REACTION CONTROL SYSTEM COMMAND LOGIC
45° JET CLUSTER LOCATION, 16 JET CONFIGURATION
NORMAL OPERATION

TRANSLATION ALONG VEHICLE AXES:

$\overset{X}{\text{S}}$, Y, Z
Subscript 1 - Positive
Subscript 2 - Negative
Prime Denotes NOT Condition
Star Denotes Jet Selection

ROTATION ABOUT VEHICLE AXES:

P - About X axis
Q - About Y axis
R - About Z axis
Subscript 1 - positive
Subscript 2 - Negative

$$T_1^* = X_1'(Q_2+R_1)$$
$$T_2^* = X_1(Q_2'R_1' + Q_1 + R_2)$$
$$T_3^* = Z_2 + Z_1'P_2(Y_1+Y_2)$$
$$T_4^* = Y_2 + P_1(Z_1+Z_2+Y_1')$$
$$T_5^* = X_2(Q_2'R_2'+Q_1+R_1)$$
$$T_6^* = X_2'(Q_2+R_2)$$
$$T_7^* = Z_1 + Z_2'P_1(Y_1+Y_2)$$
$$T_8^* = Y_2 + P_2(Y_1'+Z_1+Z_2)$$

$$T_9^* = X_1'(Q_1+R_2)$$
$$T_{10}^* = X_1(Q_1'R_2'+R_1+Q_2)$$
$$T_{11}^* = Z_1 + P_2 Z_2'(Y_1+Y_2)$$
$$T_{12}^* = Y_1 + P_1(Z_1+Z_2+Y_2')$$
$$T_{13}^* = X_2(Q_1'R_1'+R_2+Q_2)$$
$$T_{14}^* = X_2'(Q_1+R_1)$$
$$T_{15}^* = Z_2 + P_1 Z_1'(Y_1+Y_2)$$
$$T_{16}^* = Y_1 + P_2(Y_2'+Z_1+Z_2)$$

TO ENABLE JETS TO FIRE:

$$|\phi_\epsilon'| > n \longrightarrow P=1$$
$$|\theta_\epsilon'| > n \longrightarrow Q=1$$
$$|\psi_\epsilon'| > n \longrightarrow R=1$$

THRUST EACH JET:

$$T_j = T_j^* T_i^c \frac{1}{\tau s+1}, \quad j = 1 \rightarrow 16$$
$$T_i^c = k(\Phi_i - n) - b, \quad n \le \Phi_i \le e$$
$$T_i^c = 100 \text{ LBS.}, \quad \Phi_i > e$$

FINAL SIMPLIFIED REACTION CONTROL SYSTEM

COMMAND LOGIC

Conditions: X = Y = Z = 0, No translation command logic has been included in the simulation. All Y and Z translation commands are assumed to act directly at the center of gravity and induce not moments.

CORRECT VEHICLE LOGIC	ANALOG COMPUTER SIMULATION
$T_1^* = Q_2 + R_1$	$L = \pm 2\ell\,[k(\phi'_\epsilon - n) - b] = \pm 2\ell\, T^c_{\phi'_\epsilon}$
$T_4^* = P_1$	$M = \pm 2\ell\,[k(\theta'_\epsilon - n) - b] = \pm 2\ell\, T^c_{\theta'_\epsilon}$
$T_6^* = Q_2 + R_2$	$N = \pm 2\ell\,[k(\psi'_\epsilon - n) - b] = \pm 2\ell\, T^c_{\psi'_\epsilon}$
$T_8^* = P_2$	$n =$ dead-zone
$T_9^* = Q_1 + R_2$	$b =$ bias level
$T_{12}^* = P_1$	
$T_{14}^* = Q_1 + R_1$	
$T_{16}^* = P_2$	

As can be seen by comparison of correct vehicle logic and the analog computer simulation equations, moments L, M, N are equivalent to the correct vehicle logic in that a pure pitch roll or yaw command activate a pair of reaction jets. There is , however, a slight deviation when combined pitch and vehicle yaw maneuvers are commanded. In this case the actual vehicle logic produces for this condition greater moments than the simulated vehicle. The probable occurrence of this combined frequent usage of pitch and vehicle yaw is remote and will be primarily correction inputs of short duration and transient in nature. It is not anticipated that this simplification will bias the results of the Phase A lunar landing simulation. A scheme for updating the simulation logic has been determined and could be easily implemented if desired.